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Practical Exercise for the IAEA Workshop on Safety Assessments at Risø (Denmark)

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by

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Remark:

The views expressed in this report are those of the authors and do not necessarily reflect the views and policies of IAEA

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It is asserted, that this report has been prepared to best knowledge, impartially and without directive with respect to the result.

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1. INTRODUCTION

It is the aim of this exercise to prepare a valid safety assessment for a small part of decommissioning work in the research reactor DR-3 in Risø, Denmark. The safety assessment is based on realistic radiological data as well as realistic assumptions on the decommissioning work to be carried out. Three components have been selected:

- dismantling of one heat exchanger as a part of the primary circuit,
- dismantling of the fuel flask (fuelling machine),
- demolition of the biological shield with two different techniques.

The participants have time for inspection of the RR and the relevant components. They receive all required drawings, information on the envisaged dismantling procedures and all necessary radiological and other data as far as available, having to fill data gaps by reasonable assumptions. They are asked to perform an assessment guided by a list of questions, to perform simple calculations and to prepare a short report and presentation showing the task, the data, the approach and the results. They are asked to hold this presentation during the workshop.

The present document provides the required information for performing the practical exercise. However, basic data on the reactor DR-3 and on its radiological characterisation are not reproduced in this document. The required data are contained in the report “The DR3 Characterization Project” [DAN 06], which should be studied by the participants of this workshop.

2. DESCRIPTION OF THE REACTOR

2.1 The Reactor

The DR3 research reactor was a 10 MW_{th} heavy water moderated and cooled reactor of the DIDO type. This reactor type was developed at the Atomic Energy Research Establishment at Harwell, Oxfordshire, in the United Kingdom. It used enriched uranium metal fuel, and heavy water as both neutron moderator and primary coolant. There was also a graphite neutron reflector surrounding the core. The DIDO reactor was designed to have a high neutron flux, which made it suitable for testing of materials and irradiation experiments. This also allowed for the production of intense beams of neutrons for use in neutron diffraction.

There have been six reactors of this design around the world, in particular:

DIDO and PLUTO at the Atomic Energy Research Establishment (AERE), Harwell (UK),

Dounreay Materials Testing Reactor (DMTR) at Dounreay Nuclear Power Development Establishment in Scotland (UK),

HIFAR at the ANSTO Research Establishment at Lucas Heights near Sydney (Australia),

FRJ-II at the Jülich Research Centre (Germany), and

DR-3 at Risø National Laboratory (Denmark).

Initially, the DR-3 reactor used 80% enriched uranium as fuel, but later it was converted to the use of 20% enriched uranium. It went critical for the first time on 16 January 1960. After a period of low power tests it was gradually brought to full power from the beginning of August to the middle of November 1960. Hereafter it started regular operation. It was used for materials testing, for neutron beam experiments, for isotope production and silicon irradiation. In the spring of 1999 an increase of the tritium level in the CO_2 system of the graphite reflector was observed. The reason for this increase turned out to be a corrosion leak at the tank drain tube. The leak was repaired from December 1999 to February 2000, when operation was resumed. However, the reactor was finally shut down in the middle of March 2000 to permit a thorough examination of the reactor tank. This examination and other considerations resulted in a decision in September 2000 by the Risø management to close down the DR3 permanently together with the other nuclear facilities at Risø National Laboratory. [DAN 06]

The ventilation system of the DR-3 containment maintains an under-pressure of about 70 mm water. The exhaust air is cleaned by HEPA-filters and is discharged through a 23 m high ventilation chimney. Measurements to record releases of particulates and tritium through the chimney are performed after the HEPA-filters. The ventilation system is still operating and will be maintained during most of the decommissioning. [NBH 03].

2.2 The Site and the Surroundings

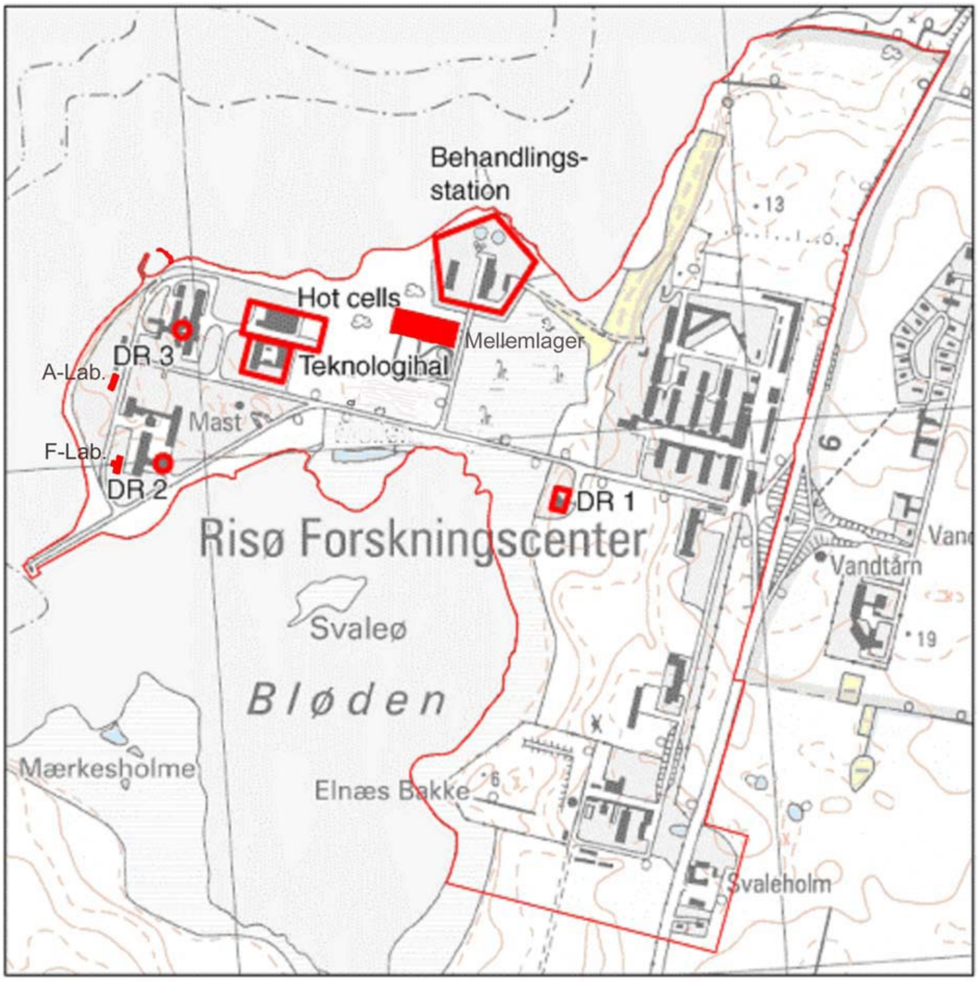
A description of the Risø site and the surroundings is contained in the Report of the Danish Government that had to be prepared under Article 37 of the Euratom Treaty to inform EU Member States on possible impacts decommissioning of the nuclear facilities on the site could have on neighbouring countries [NBH 03]. The following description is taken from this report. For practical reasons, it concentrates on only those pieces of information that are relevant to preliminary safety assessments to the general public.

The Risø site covers an area of about 240 ha and consists of the Risø peninsula with adjacent land on the eastside of Roskilde Fjord. Gently undulating landscape with agricultural fields, a few relatively small forests, widely distributed farm buildings, roads, villages and towns constitutes the surroundings. Figure 2.1 shows the Risø site in the middle of Zealand about 6 km north of Roskilde and 30 km west of Copenhagen. Figure 2.2 shows the site of the research centre in greater detail. The location of DR-3 within the research centre is visible in Figure 2.3.

Figure 2.1: The Risø site and the surroundings

Figure 2.2: The Risø research centre

Figure 2.3: The layout of the Risø research centre



The local meteorological conditions at Risø are determined by the position of the site as a peninsula into Roskilde Fjord and in general in an area with low relief. The climate in Denmark is northern temperate dominated by western winds and many passing front systems of high and low pressures. Normally the winters are mild and the summers are cool, but occasional periods with eastern wind may introduce a more continental climate.

The hydrological situation around the Risø research centre is characterised by the fact that the water surrounding the peninsula is a fjord with connection to the Kattegat (between North Sea and Baltic Sea) in the north and that the groundwater is flowing from east to west into the direction of the coast. Furthermore, there is no risk of flooding from rainfall or snow melting. The highest flood level measured at Roskilde Harbour is 1.65 m above normal fjord level. Such increased levels are mainly due to prolonged wind pressure. They will not be sufficient to influence the existing nuclear facilities.

The seismic activity of the area is very low. The largest earthquake was measured with magnitude 3 on the Richter scale.

With respect to the safety assessment, these data can be summarised as follows:

- As can be seen from Figure 2.1, the nearest settlements are located about 1.000 m to the east of DR-3, i.e. in the main wind direction.

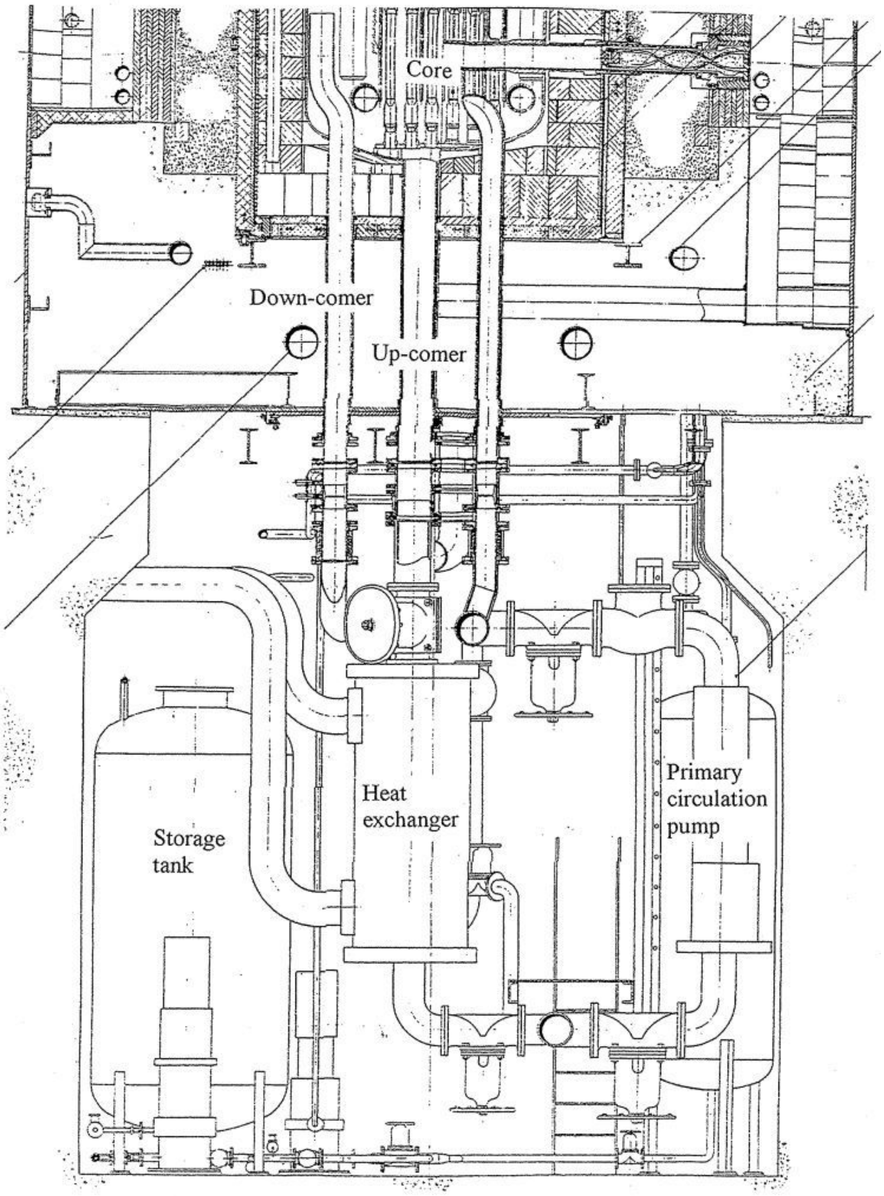
- A large part of the area is in agricultural use. This means that local food production and food consumption has to be taken into account.
- The groundwater is not flowing towards any settlement. In addition, there are no relevant surface waters. There is therefore no relevance for water pathways.
- It is extremely unlikely that an earthquake may occur during the decommissioning phase that could damage the buildings of DR-3.

3. Description of the Three Cases

3.1 Dismantling of a Heat Exchanger

3.1.1 Situation and Data

Figure 3.1: View of the heavy water room below the reactor block with the out-of-core part of the primary circuit



Measurements of the dose rate in the heavy water room below the reactor block were performed, in particular on the surface of the main components of the primary circuit. The DR3 is provided with three up-comer tubes, situated around the axis of the reactor tank and entering the reactor tank below the grid plate. The heavy water was pumped up through the up-comer tubes and the grid plate to the fuel elements. Four down-comer tubes are situated around the up-comer tubes. Through these four tubes the heavy water flowed from the reactor tank to the pumps and heat exchangers.

Just below the ceiling of the heavy water room the up- and the down-comer tubes are divided into four tube sections (see Figure 3.2). The radiation level at these sections is given in Table 3.1.

Table 3.1: Dose Rate at the Top Sections of Up- and Down-Comer Tubes [µSv/h]

	Up-Comers			Down-Comers			
Section	**UC1**	**UC2**	**UC3**	**DC1**	**DC2**	**DC3**	**DC4**
Top section	2100	1800	700	800	1300	1500	1100
Second Section	1300	1500	950	450	650	960	600
Third section	350	450	350	60	150	200	100
Bottom section	200	50	200	60	150	60	70

From Table 3.1 it is seen that the dose rate level decreases rapidly with the distance to the ceiling of the room. The reason is undoubtedly that the dose rate at the top of the up- and down-comer tubes in the heavy water room is primarily due to the radiation from sources in or around the reactor tank.

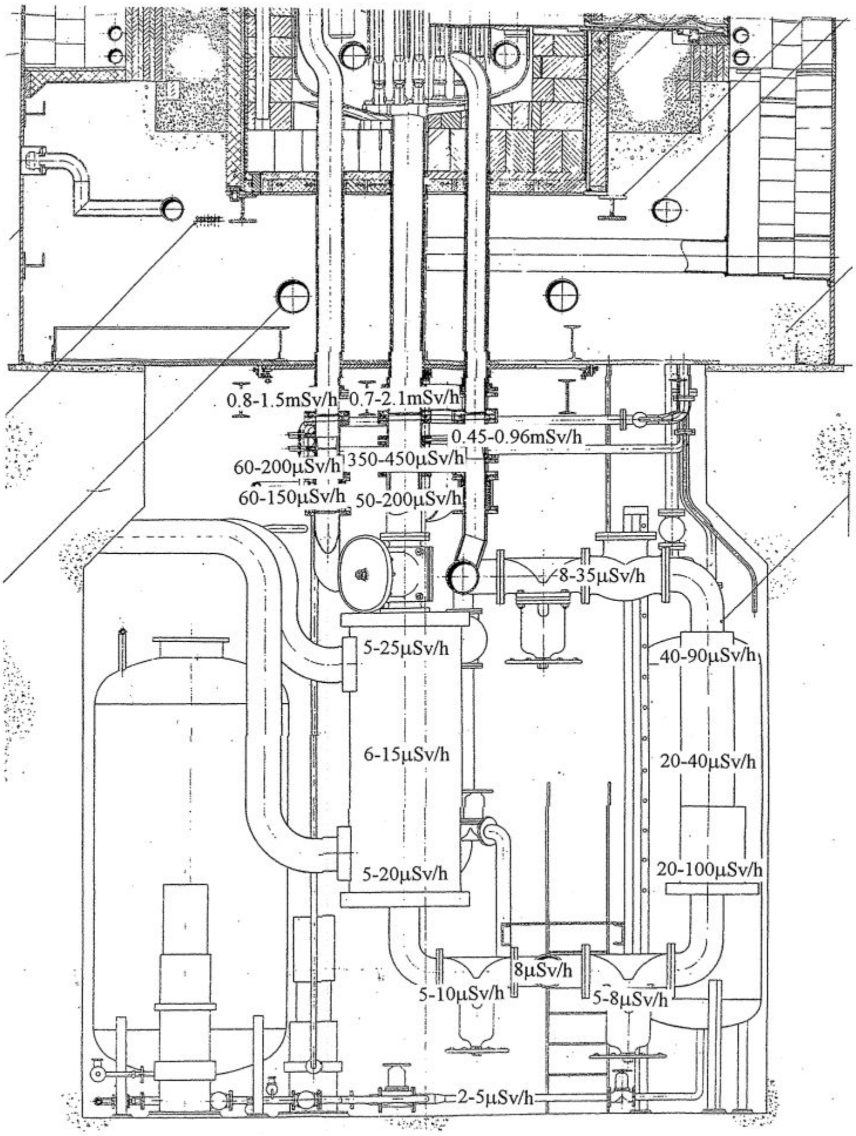
The drainage of the heavy water of the primary circuit has also resulted to an increase of the radiation level around the top of the up- and down-comer tubes.

The dose rates at the surface of the three main heat exchangers, 1E1/1, 1E1/2 and 1E1/3, are given in Table 3.2

Table 3.2: Dose Rate at the Three Main Heat Exchangers [µSv/h]

Part of component	Heat exchanger 1E1/1	Heat exchanger 1E1/2	Heat exchanger 1E1/3
Top of heat exchanger	10-20	10-25	5-25
Middle of heat exchanger	8-15	8-11	6-10
Bottom of heat exchanger	7-20	10-15	5-10
Valve at heat exchanger inlet	10	8	5

Figure 3.2 Dose rates at the surface of various components in the heavy water room below the reactor block.



In addition to dose rates, measurements of the contamination inside the primary circuit have been made. In connection with the opening of the primary circuit of the DR3 to remove the flaps of the three check valves of the circuit, smear tests were carried out in the tubes at both sides of the valves to get an idea of the contamination of the inner surface of the circuit. The activities measured by the smear test are presented in Table 3.3. From this table it is seen that Co-60 was found in all tests and Zn-65 in some, while no Cs-137 was detected.

Table 3.3: Contamination of the Primary Circuit

Component	Activity Co-60 per test [Bq]	Activity Zn-65 per test [Bq]
Valve 1057 – towards pump 1P1A	$1.29\ 10^{4}$	-
Valve 1057 – towards valve 1056	$6.03\ 10^{3}$	-
Valve 1070 – towards pump 1P1B	$2.60\ 10^{2}$	3.91
Valve 1070 – towards valve 1070	$1.07\ 10^{3}$	-
Valve 1078 – towards pump 1P1C	$2.38\ 10^{2}$	-
Valve 1078 – towards valve 1077	$3.70\ 10^{4}$	$1.50\ 10^{4}$

3.1.2 Dismantling Sequence

Segmenting can take place with mechanical techniques like sawing or thermal techniques like plasma arc cutting. There are significant differences in the cutting speed and aerosol generation of both types of techniques.

Before the heat exchanger can be removed, the pipes to which it is connected have to be cut. Both open ends have then to be sealed in order to avoid inner surfaces of the primary circuit being open to the plant atmosphere. It must be ensured that the heat exchanger can be removed in one piece from its current position. Segmenting of the component will then be carried out ex situ in a separate area. The details of lowering the heat exchanger on some kind of carriage on which it is transferred to the segmenting are not dealt with in this context.

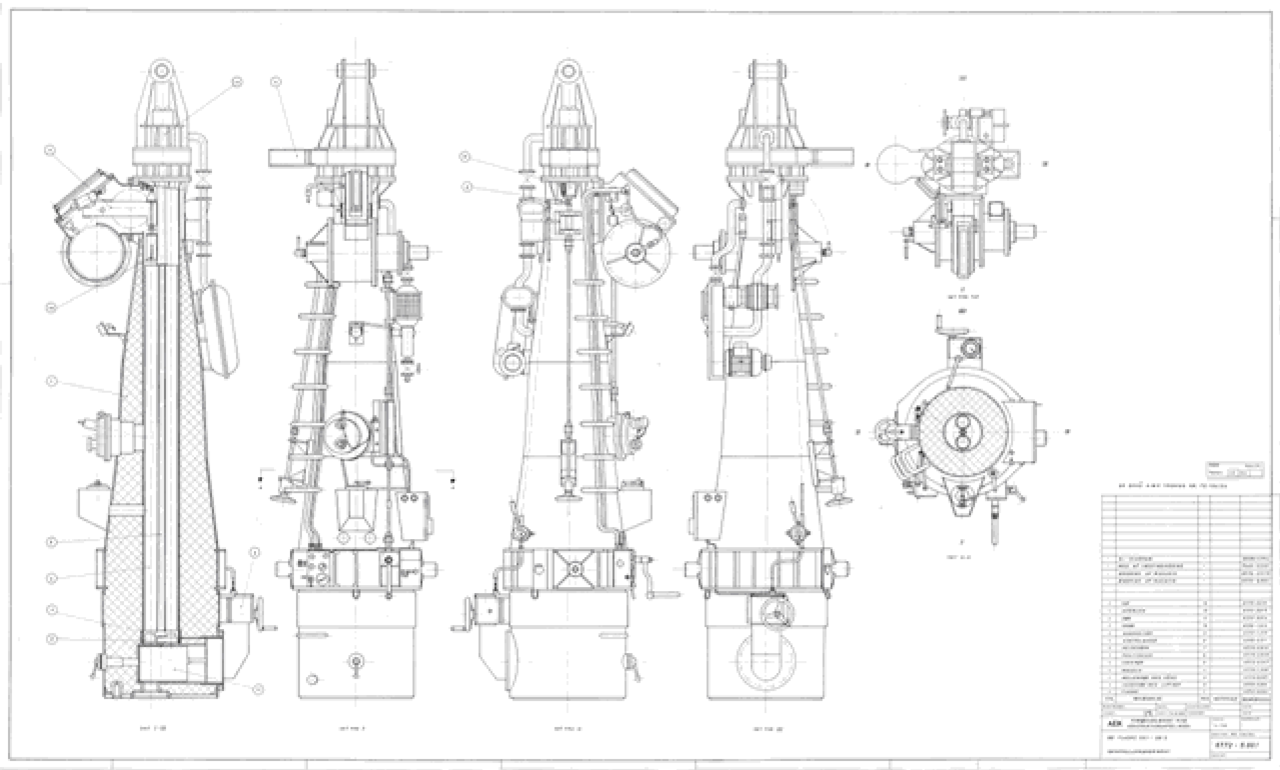
Segmenting of the component is carried out in a temporarily erected tent which is connected to a ventilation and filtration device. This allows use of manual thermal cutting techniques for fast and easy segmenting.

3.2 Dismantling of the Fuel Flask

3.2.1 Situation and Data

The fuelling machine served for loading and unloading the fuel elements from the reactor core and for transport of the fuel elements to the fuel container.

Figure 3.3: The fuel flask



The radiological characterisation of the fuel flask has been performed by Danish Decommissioning in September 2010. The relevant data are shown in Table 3.4. The nuclide vector can be assumed to be dominated by Co-60.

Table 3.4: Radiological data of the fuel flask

Measurement	Location	Value
Contamination measured by smear test	exterior surface of the flask	4 Bq/m²
	bottom of the flask	19 Bq/m²
	bottom at the guideway	262 Bq/m²
	inner surface of the flask	$<1 \cdot 10^4$ Bq/m²
Dose rate measured by dose rate meter	at closed bottom door	0,6 µSv/h
	20 cm inside the flask	17 µSv/h
	ca. 180 cm inside the flask	750 µSv/h

3.2.2 Dismantling Sequence

In principal, the same considerations with respect to dismantling of the fuel flask apply as for segmenting of the heat exchanger in section 3.1.2. A final dismantling sequence has not yet been developed by Danish Decommissioning. In general, the dismantling will take place with the flask in a horizontal position. It can be assumed that the cylindrical flask will be cut into ring segments.

3.3 Demolition of the Biological Shield

3.3.1 Situation and Data

The biological shield surrounds the reactor and serves to reduce the dose rate during operation of the reactor. The reactor block is characterised as follows in [DAN 06]:

- The reactor block, neglecting the top part, which is primarily steel, has the shape of a box with a length of about 6.5 m and a height of about 5.4 m. The volume of the block is about 230 m³.
- The volume of the steel tank with the thermal shield, the graphite reflector, the reactor tank and the reactor lid is about 30 m³, and the volume of the steel ball concrete ring and the shielding plates around the horizontal experimental tubes is about 11 m³.
- The remaining volume consists mostly of barite concrete and amounts to about 190 m³. However, this volume includes the vestibule boxes at the outer ends of the horizontal tubes and the tubing in the reactor block. With a density of the barite concrete of about 3.4 g/cm³, the amount of barite concrete is estimated to about 650 Mg.

Figure 3.4 shows a vertical cross section of the reactor block, Figure 3.5 a horizontal cross section.

Figure 3.4: Vertical cross section of the reactor block

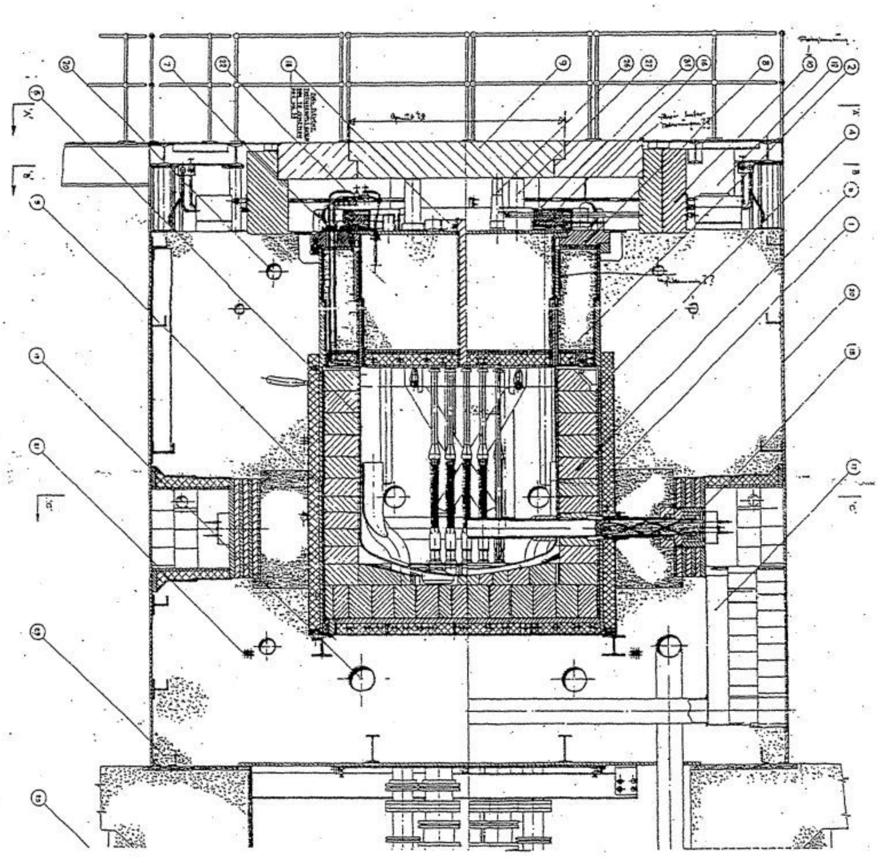
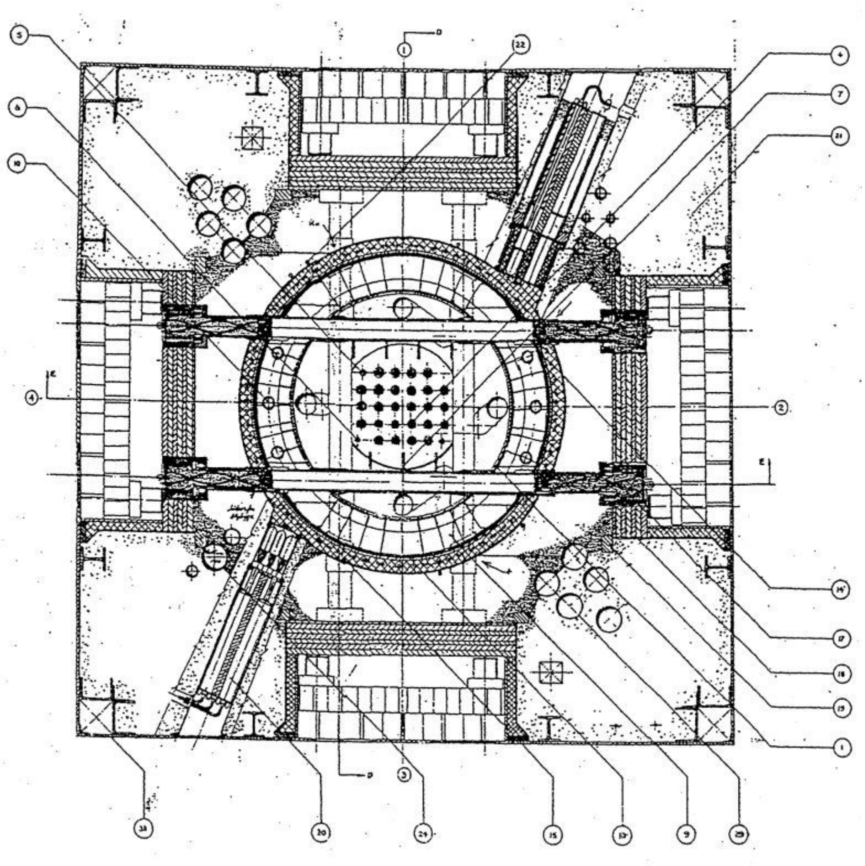


Figure 3.5: Horizontal cross section of the reactor block



During drilling experiments in the concrete of the biological shield, the radiologically relevant radionuclides that could be detected by gamma spectrometry were Ba-133, Eu-152, Eu-154 and Co-60. Two horizontal boreholes (termed V1 and V2 in [DAN 06]) were drilled, segmented into small samples and measured. Figure 3.6 shows the mass related activities of these radionuclides as a function of depth for V1, Figure 3.7 for V2. The gradient of the activity in the barite concrete becomes clearly visible. No total activity in the biological shield has been derived from the results presented in [DAN 06], as the number of samples was deemed to be too small to be representative for the entire biological shield.

Figure 3.6: Activities of samples from borehole V1 as a function of depth

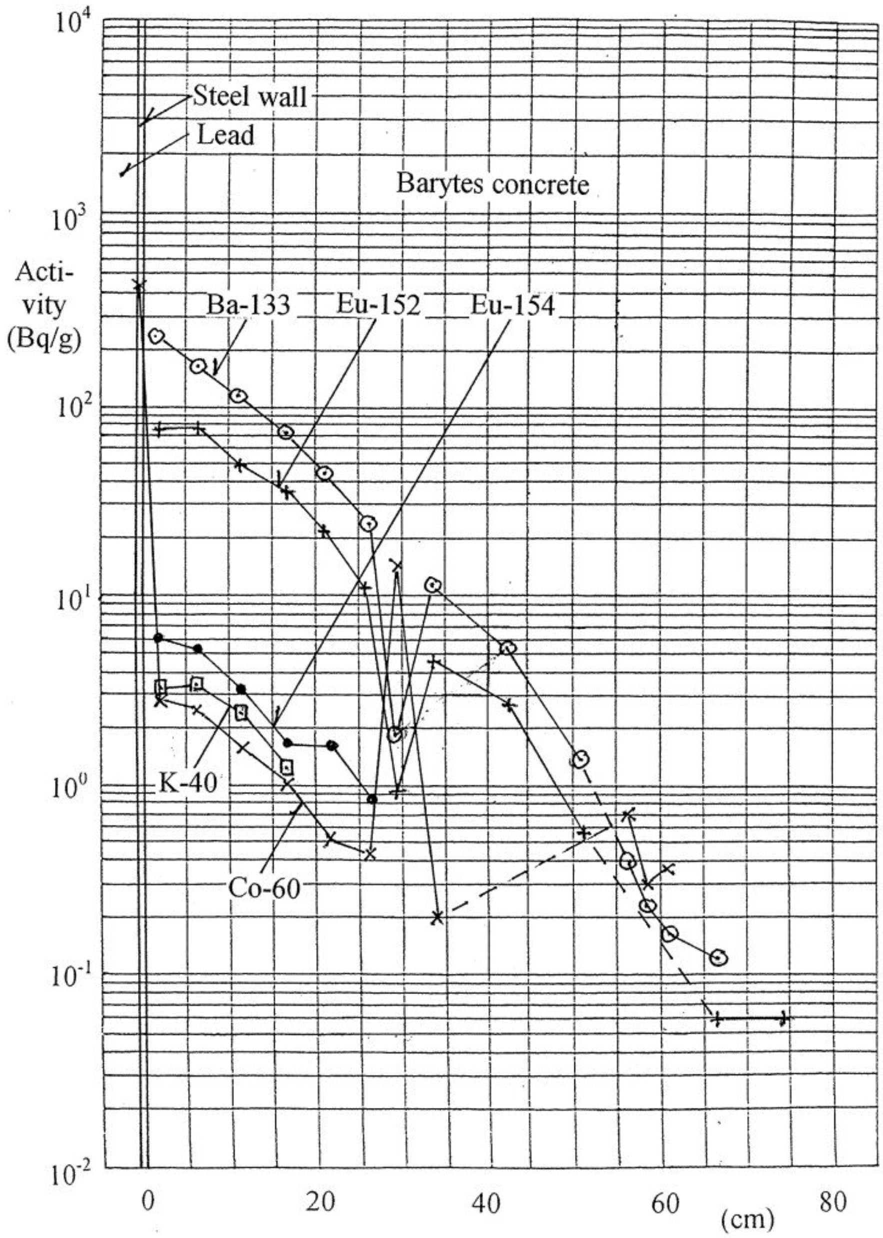
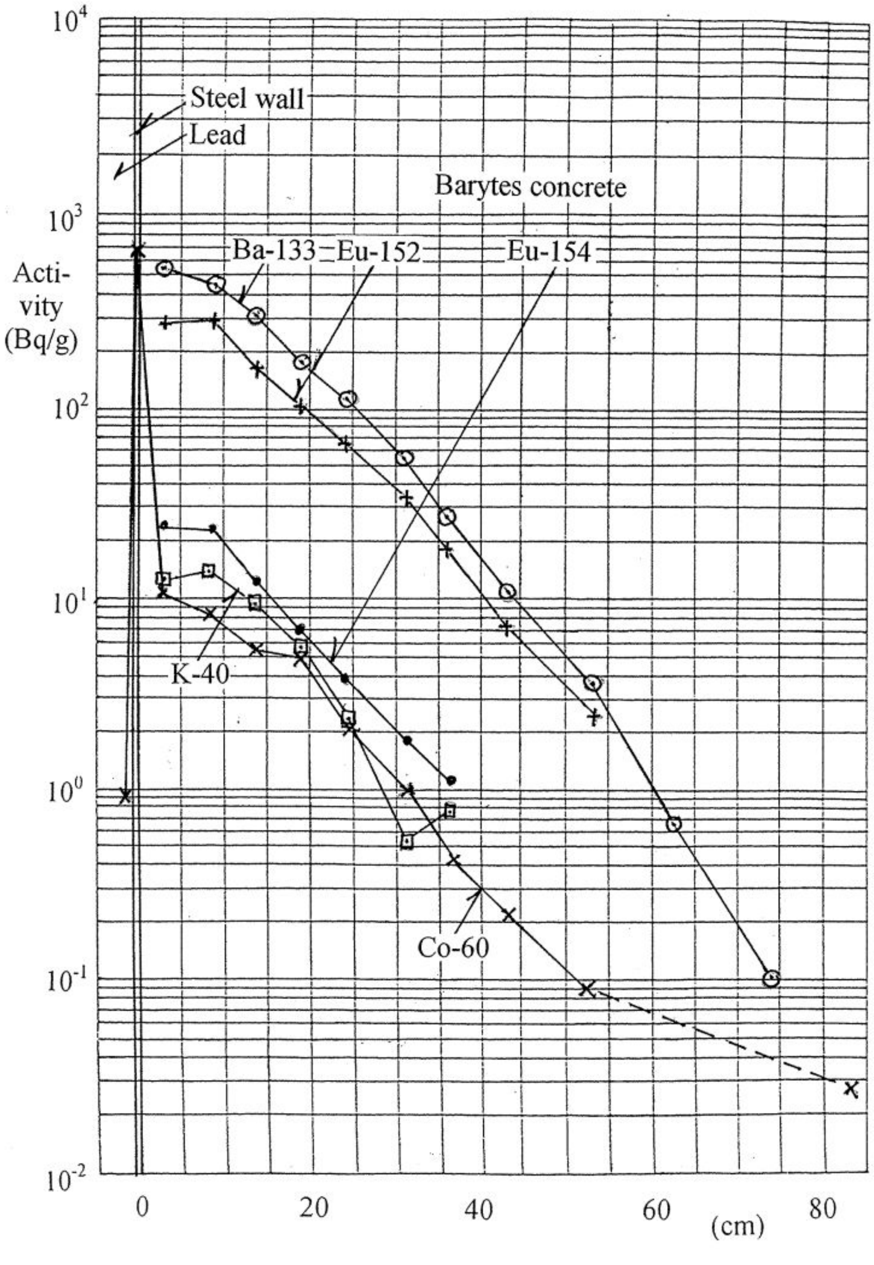


Figure 3.7: Activities of samples from borehole V2 as a function of depth



Dose rates at various samples from boreholes have been measured between < 0.05 µSv/h (samples from the outer surface) and up to about 100 µSv/h (samples from the internal side).

Based on comparison with a similar reactor at Harwell (UK), the entire activity content of the concrete of the biological shield has been estimated as shown in Table 3.5 (Risø report 1250). These values are valid for 10 a after shutdown.

Table 3.5: Estimation of the activity contents of the concrete of the biological shield

Radionuclide	Activity [GBq]
H-3	7,000
Fe-55	70
Co-60	40
Ni-63	20
Ba-133	460
Eu-152	320
Eu-154	32

3.3.2 Dismantling Sequence

The biological shield will be dismantled after the rest of the reactor block, i.e. most of the metallic structures, all experimental tubes and all circuits will have been removed. The biological shield is usually one of the last structures to be dismantled, as it provides structural support to the reactor components and shielding.

Up to now, no detailed dismantling sequence has been envisaged for the biological shield. It is possible to demolish the concrete structure in two ways:

- Cutting of blocks by diamond wire cutting. The diamond wire is used to first perform vertical cuts in the concrete structure that are then complemented by horizontal cuts creating blocks that can be lifted and removed by the crane in the reactor hall. These blocks can be further reduced in size by additional cuts across their width. Diamond wire cutting can be carried out in a dry or wet process. Dry cutting leads to a slight increase in wear of the cutting wire, but avoids creation of liquid radioactive waste. The resulting dust is sucked off at the point where the wire leaves the cut. Wet cutting uses water or some lubricant for lubrication and cooling, reducing wear of the wire, but giving rise to liquid radioactive waste that has to be treated and conditioned. In both cases, segmenting of the reinforcement steel is possible.
- Demolition of the structure with a pneumatic chisel operated from a hydraulic shovel (e.g. a Brokk). The machine is placed on a temporary platform or scaffold next to the concrete structure. The chisel is attached to the arm of the machine breaking and removing the concrete from top to bottom. The reinforcement steel has to be cut separately e.g. by hydraulic shears that can also be attached to and operated by the machine. The chiselling process gives rise to large amounts of dust that has to be controlled. This is usually done by erecting an encasement around the machine and the working area to which temporary ventilation and filtration is attached. Brokk machines can be converted to remote operation so that no person needs to be present in the control cabin.

3.4 Airborne Releases

The following general estimate of airborne releases is taken from an overview provided by Risø.

At present, the containment at DR 3 and the cavities in the biological shield are ventilated and the ventilation air is discharged through a 23 m high ventilation stack after filtration through HEPA-filters (efficiency > 99 %). The discharge from the reactor to the atmosphere is presently only tritium, probably from the heavy water trapped in the graphite after the leak in the primary cooling system during 1999 - 2000. The tritium discharge to the atmosphere during 2001 was measured to about 1,000 GBq and it is slowly decreasing.

The main decommissioning activities, which could potentially cause additional discharges to the atmosphere, are the dismantling and fragmentation of the active reactor construction components and the subsequent processing and packing of the resulting dry waste. The major radionuclides in the construction parts are H-3 (36 TBq), C-14 (0.2 TBq), Co-60 (100 TBq), Ba-133 (2 TBq) and Eu-152+154 (2 TBq). The activities indicated in parenthesis refer to the year 2000 when also large amounts of Fe-55 and Zn-65 were present. At the time of decommissioning of DR 3, the activity of Fe-55 and Zn-65 has decayed, however, to insignificantly low levels.

Values for releases of the radionuclides present in the reactor components during decommissioning are difficult to estimate. The major part of the activity is fixed within the components as activation products, and it is therefore assumed that an annual fractional release rate of 0.1 % of the inventory per year is rather conservative.

Due to filtration through HEPA-filters a maximum of 1 % of this fractional release rate is assumed to penetrate the filters. A filtered release rate of 0.1 % per year corresponds to the following expected maximum annual discharges of contamination and activation products (the tritiated heavy water release is not diminished by filtration, whereas the tritium content in concrete is filtrated):

H-3:	0.36 GBq/a	and 1,000 GBq/a from heavy water in graphite
C-14:	0.002 GBq/a	
Co-60:	1 GBq/a	
Ba-133:	0.02 GBq/a	
Eu-152 and Eu-154:	0.02 GBq/a	

3.5 Release rates from thermal cutting operations

A task often required is to estimate the airborne activity concentration due to the operation of cutting techniques. The activity that actually will become airborne in specific circumstances depends on many parameters, but the following simple estimate can be used to calculate a first order-of-magnitude value of the airborne activity concentration.

The most important parameter is the release rate *f* during cutting. This value describes the release in Bq per m cut length as a function of the surface contamination Bq/cm². The cutting speed *r* (in m/h) is relevant as a fast cutting speed will obviously lead to a higher release than a slow one. Assuming that the airborne activity will spread over the immediate vicinity of the cut, then the only removal process will be the air exchange in the room. The higher the air exchange rate *W*, the lower the resulting activity concentration in the air. This leads to the following equation:

$$F = \frac{f \cdot r}{W}$$

Typical values for these parameters are given in Table 3.6. These are based on actual measurements presented in [GAR 96]. Typical values for release rates are between 0.1 and 20 (Bq/m)/(Bq/cm²), so that an average of 3.3 (Bq/m)/(Bq/cm²) has been chosen (note that only the activity situated on the line of cutting, the kerf width, will be resuspended into the air). The cutting speed of 4 m/h is suitable for rather slow cutting operations at pipes and components in situ, while higher values of several 10 m/h would be more pertinent to cutting scrap. The air exchange rate strongly depends on the room size and the capacity of the ventilation. Here it has been assumed that the air in heavy water room will be exchanged about once per hour (a conservatively low assumption), so that 60 m^3/h is a suitable value. Inserting these values into the formula above, the airborne activity per surface contamination is 0.02 $(Bq/m^3)/(Bq/cm^2)$. This means that during cutting operations, it is reasonable to assume that the airborne activity is about 0.2 Bq/m^3 if the surface contamination is 1 Bq/cm^2.

Table 3.6: Calculation of the activity release into the atmosphere for manual segmenting of contaminated metal surfaces

Parameter	Symbol	Unit	Typ. value	Possible range
Release rate	f	$(Bq/m)/(Bq/cm^2)$	3.3	0.1 – 20
Cutting speed	r	m/h	4	1 – 60
Air exchange rate	W	m^3/h	60	depend on room size and ventilation
Airborne activity per surface contamination	F	$(Bq/m^3)/(Bq/cm^2)$	0.2	$3\cdot10^{-5}$ – 1.2

4. Questions and Topics for the Practical Exercise

4.1 Before you start

- Choose one of the three cases. All cases are alike concerning the types and complexity of safety assessments.
- What you need: A copy of the DeSa report of IAEA, a copy of Safety Report Series No. 19: “Generic models for use in assessing the impact of discharges of radioactive substances to the environment” of IAEA, documentation of DR3 as provided by Risø National Laboratory or by Danish Decommissioning, paper and pencil (or even better: a computer and printer).
- This assessment is not a complex dose assessment that would be carried out in the detailed planning phase when a certain decommissioning step is prepared. This assessment would be more pertinent to a situation when you as a health physicist would be asked by your plant manager: “Could we perform this particular decommissioning task without radiological problems for our workforce and for the general public in the neighbourhood? And which of the two (or three) cutting techniques would be better in your opinion from a radiological point of view?”
- The questions for all three cases are there to guide you through the four parts of the assessment, that means doses to workers and doses to the public, caused by normal working conditions and by accidents. It is not necessary to answer them point by point, but your answers to each question (#1 to #4) should cover all aspects addressed in the subitems. The last question (#5) is intended to summarise your assessment so that you are able to answer the question whether the envisaged work could be carried out safely. This is also the concise answer to the above questions of your plant manager.
- The assessment is designed in such a way that it could be handled by a person or a small team familiar with radiological assessments in about 2 days working time. If you finish faster, then please revisit the points of your assessments where you define working conditions and other parameters relevant to your scenario.
- After you have completed the assessment, please prepare a simple and short presentation in which you present your approaches, assumptions and results to other working groups dealing with the other two cases.

4.2 Questions for Case 1

The following questions should be dealt with in the safety assessment by the group performing the safety assessment for Case 1 – dismantling of a heat exchanger:

1. Normal operation, workers:
   a) What are the risks to the workers and the associated potential exposure pathways during normal operation? Please provide a list of hazards that you think might be relevant. Which are the most important ones? Why?

b) Consider the two options for segmenting of the heat exchanger: mechanical cutting techniques (in particular sawing, rather slow, no aerosols) and thermal cutting techniques (in particular plasma arc cutting, fast, large amount of aerosols). Structure the work into reasonable work packages for both options. Identify situations that can be regarded as bounding for each work package (neglect the transport of the heat exchanger from the heavy water room to the segmenting area). Prepare scenarios describing the possible exposure situations for these situations, in particular taking account of the inhalation pathway and protective measures against inhalation and of the significant differences in exposure time. How would you calculate the doses to the personnel in each case?

c) Perform the dose calculations and give a bounding estimate for the doses that workers may receive for both options. The result can be regarded as a bounding estimate of the doses to workers during the planned work.

d) Which of the two options for dismantling of a heat exchanger (thermal or mechanical cutting techniques) is the best one from a radiological point of view? – Consider only this technique for the subsequent questions.

2. Incidents or accidents, workers:

   a) What incidents or accidents (with radiological consequences) could happen to workers during the work, taking also the confined space in the heavy water room and the use of thermal cutting techniques in the tent into consideration? How would you rank their probability for occurrence? Consider external exposure, inhalation of dust and aerosols.

   b) Which exposure scenarios could be used in each case? Can you identify bounding scenarios? Which exposure pathways have to be taken into account?

   c) Perform the dose calculations for these bounding scenarios. Which scenario leads to the highest dose?

3. Normal operation, public:

   a) Which are potential exposure pathways by which the general public could be exposed? Take into account external exposure, inhalation of aerosols / dust, direct ingestion and secondary ingestion pathways.

   b) Give an estimate for the source terms relevant to these exposure pathways.

   c) Provide a very simple estimate of the dose to a person of the general public on the basis of the identified exposure pathways and the source term (upper bound). Is it necessary to perform an in-depth analysis of the exposure to the public? Why?

4. Incidents or accidents, public:

   a) Consider a situation where accidentally an internal contamination inside the heat exchanger that has not been noted previously is released to the plant atmosphere and from there to the environment because the filter is not working for some reason. What would be a suitable assumption for a source term?

   b) Perform a simple calculation of doses to the public for this scenario assuming unfavourable meteorological conditions (i.e. conditions leading to a high exposure).

5. Summary

   a) Provide a summary of the results under points 1 to 4 indicating the overall assessment of safety for the envisaged work.

4.3 Questions for Case 2

The following questions should be dealt with in the safety assessment by the group performing the safety assessment for Case 2 – dismantling of the fuel flask:

1. Normal operation, workers:

   a) What are the risks to the workers and the associated potential exposure pathways during normal operation? Please provide a list of hazards that you think might be relevant. Which are the most important ones? Why?

   b) Consider the two options for segmenting of the fuel flask: mechanical cutting techniques (in particular sawing, rather slow, no aerosols) and thermal cutting techniques (in particular plasma arc cutting, fast, large amount of aerosols). Structure the work into reasonable work packages for both options. Identify situations that can be regarded as bounding for each work package. Prepare scenarios describing the possible exposure situations for these situations, in particular taking account of the inhalation pathway and protective measures against inhalation and of the significant differences in exposure time. How would you calculate the doses to the personnel in each case?

   c) Perform the dose calculations and give a bounding estimate for the doses that workers may receive for both options. The result can be regarded as a bounding estimate of the doses to workers during the planned work.

   d) Which of the options for segmenting of the fuel flask (mechanical or thermal) is the best one from a radiological point of view? – Consider only this technique for the subsequent questions.

2. Incidents or accidents, workers:

   a) What incidents or accidents could happen to workers during the work, taking the weight of the component and the need for supporting pieces that have been cut into account? How would you rank their probability for occurrence? Consider external exposure and inhalation of aerosols.

   b) Which exposure scenarios could be used in each case? Can you identify bounding scenarios? Which exposure pathways have to be taken into account?

   c) Perform the dose calculation for these bounding scenarios. Which scenario leads to the highest dose?

3. Normal operation, public:

   a) Which are potential exposure pathways by which the general public could be exposed? Take into account external exposure, inhalation of aerosols / dust, direct ingestion and secondary ingestion pathways.

b) Give an estimate for the source terms relevant to these exposure pathways.

c) Provide a very simple estimate of the dose to a person of the general public on the basis of the identified exposure pathways and the source term (upper bound). Is it necessary to perform an in-depth analysis of the exposure to the public? Why?

4. Incidents or accidents, public:

a) Consider a situation where accidentally an internal contamination inside the fuel flask that has not been noted previously is released to the plant atmosphere and from there to the environment because the filter is not working for some reason. What would be a suitable assumption for a source term?

b) Perform a simple calculation of doses to the public for this scenario assuming unfavourable meteorological conditions (i.e. conditions leading to a high exposure).

5. Summary

a) Provide a summary of the results under points 1 to 4 indicating the overall assessment of safety for the envisaged work.

4.4 <u>Questions for Case 3</u>

The following questions should be dealt with in the safety assessment by the group performing the safety assessment for Case 3 - demolition of the biological shield:

1. Normal operation, workers:

a) What are the risks to the workers and the associated potential exposure pathways during normal operation? Please provide a list of hazards that you think might be relevant. Which are the most important ones? Why?

b) Consider the three options for demolition of the biological shield (wet and dry diamond wire cutting and hydraulic shovel with a pneumatic chisel). Structure the work into reasonable work packages for the three options. Identify situations that can be regarded as bounding for each work package. Prepare scenarios describing the possible exposure situations for these situations. How would you calculate the doses to the personnel in each case? Make an estimate of the activity and its spatial distribution from the data reported in section 3.3.1. Estimate the dose distribution around the biological shield from these activity data.

c) Perform the dose calculations and give a bounding estimate for the doses that workers may receive for all three options. The result can be regarded as a bounding estimate of the doses to workers during the planned work.

d) Which of the three options for demolition of the biological shield (wet and dry diamond wire cutting and hydraulic shovel with a pneumatic chisel) is the best one from a radiological point of view? – Consider only this technique for the subsequent questions.

2. Incidents or accidents, workers:

a) What incidents or accidents could happen to workers during the work? How would you rank their probability for occurrence? Consider external exposure, inhalation of dust and skin contamination.

b) Which exposure scenarios could be used in each case? Can you identify bounding scenarios? Which exposure pathways have to be taken into account?

c) Perform the dose calculation for these bounding scenarios. Which scenario leads to the highest dose?

3. Normal operation, public:

a) Which are potential exposure pathways by which the general public could be exposed? Take into account external exposure, inhalation of aerosols / dust, direct ingestion and secondary ingestion pathways.

b) Give an estimate for the source terms relevant to these exposure pathways. In particular, consider the H-3 content of the concrete.

c) Provide a very simple estimate of the dose to a person of the general public on the basis of the identified exposure pathways and the source term (upper bound). Is it necessary to perform an in-depth analysis of the exposure to the public? Why?

4. Incidents or accidents, public:

a) Consider a situation where accidentally a large amount of contaminated dust is created which is then partly released to the environment because the filter gets clogged and loses its function. What would be a suitable assumption for a source term?

b) Perform a simple calculation of doses to the public for this scenario assuming unfavourable meteorological conditions (i.e. conditions leading to a high exposure).

5. Summary

a) Provide a summary of the results under points 1 to 4 indicating the overall assessment of safety for the envisaged work.

5. PERFORMANCE OF THE SAFETY ASSESSMENT

5.1 Overview

This section provides some basic procedures and tools for safety assessment that are used in section 6 where the solutions to the questions of section 4 are presented.

- Section 5.2 provides a list for hazard identification

5.2 Hazard Identification

Table 5.1 provides a list of hazards that are common during work for decommissioning of nuclear installations. It tries to identify the hazards that are relevant to the three cases described in section 3 that are analysed during this workshop. The topics addressed in this table are taken from the IAEA DeSa approach [IAE 10]. The relevance of these topics has been assessed for normal decommissioning work as well as for incidents both for workers and for the general public (environmental pathways), accounting for the four columns.

The entries in Table 5.1 are a simple yes/no decision, based on the necessarily subjective approach of the author. If there is a single entry in a table cell, this entry refers to all three cases. If the cases are different with respect to the topic in the table row, three entries have been provided referring to cases 1, 2 and 3, respectively. If necessary, a short comment has been added in some table cells for better understanding.

The conclusions from this hazard identification for performing the safety assessments for these three cases are given in the text below the table.

Table 5.1: Selection of relevant hazards (following the scheme of [IAE 10], but with application to DR 3 decommissioning)

Hazards	Relevant for planned work workers	Relevant for accidents workers	Relevant for planned work public / environment	Relevant for accidents public / environment
Radiological hazards				
Direct radiation sources	yes	yes	no	no
Improper removal of shielding	yes	no	no	no
Radioactive material, incl. form: (solid, liquid, gaseous)	yes	yes	yes	yes
Criticality	no	no	no	no
Contaminated liquid, material	yes	yes	no	yes
Other radioactive sources (smoke detectors, lightning rods)	no	no	no	no
Fire/explosion hazards				
Oxygen	no	no	no	no

Hazards	**Relevant for planned work workers**	**Relevant for accidents workers**	**Relevant for planned work public / envi-ronment**	**Relevant for accidents public / envi-ronment**
Sodium	no	no	no	no
Explosive substances	no	no	no	no
Flammable gases (e.g. oxyacetylene, propane gas), liquids, dust	yes	yes	no	no
Combustible / inflammable materials (for the RR: graphite; wooden floor)	no	yes	no	yes
Compressed gases	no	no	no	no
Hydrogen generation	no	no	no	no
Overheating or fire, caused by e.g. portable heaters, overload of electrical circuits, application of cutting tech-niques	yes	yes	no	no
Electrical hazards				
High voltages	no	no	no	no
Power overload and shortcuts, power failures	no	yes (power failure during crane operation with source exposed)	no	no
Inadequately disconnected circuits / prevention against inadvertent connec-tion	yes	no	no	no
Non-Ionizing Radiation Hazards				
Non-Ionizing Radiation Sources, incl. lasers	no	no	no	no
Electromagnetic radiation (e.g. micro-waves)	no	no	no	no
High Intensity Magnetic Fields	no	no	no	no
Chemical/toxic hazards				
Chemotoxic material	no	no	no	no
Spills	no	no	no	no
Chemicals (aggressive chemicals) Remark: no acid based batteries avail-able at the reactor	no	no	no	no
Accidental mixing / combination of chemicals (e.g. in sewage systems, in decontamination work etc.)	no	no	no	no
Asbestos and other hazardous materi-als, like lead or beryllium	yes	not relevant in accident sce-nario	no	no
Pesticide use	no	no	no	no
Biohazards	no	no	no	no

Hazards	Relevant for planned work workers	Relevant for accidents workers	Relevant for planned work public / envi-ronment	Relevant for accidents public / envi-ronment
Physical hazards				
Kinetic energy	no	no	no	no
Potential energy (springs, Wigner energy in graphite)	no	no	no	no
Degraded or degrading structures, systems and components	no	no	no	no
Steam	no	no	no	no
Temperature extremes (high tempera-tures, hot surfaces, cryogenics)	no	no	no	no
High pressure (pressurized systems, compressed air)	no	no	no	no
Working environment hazards				
Working at heights (e.g. ladders, scaf-folding, man baskets)	yes (scaffolding, maintenance of crane etc.)	no	no	no
Excavations, formation of under-ground cavities (subsidence) from rain, waste degradation etc.	no	no	no	no
Vehicle traffic	no	no	no	no
Heavy lifts, material handling, heavy equipment, manual lifting, overhead hazards, falling objects, cranes	yes (lifting, cranes)	yes	no	no
Inadequate illumination	no	no	no	no
Inadequate ventilation	no	no	no	no
Noise (high noise areas and tools)	yes (concrete demolition; hearing protec-tion)	no	no	no
Dust and aerosols	yes (concrete demolition, thermal cutting tools; respira-tory protection)	no	no	no
Pinch points, sharp objects	yes (cutting operations)	no	no	no
Confined space	no	yes (in heavy water room)	no	no
Dangerous equipment, e.g. power tools, compressed gas cylinders, weld-ing and cutting, water jet cutting / decontamination, abrasive decontami-nation techniques, grinding, sawing	yes (various tools)	yes	no	no
Remote work area	no	no	no	no

Hazards	Relevant for planned work workers	Relevant for accidents workers	Relevant for planned work public / environment	Relevant for accidents public / environment
Obstruction of passageways or exits	no	no	no	no
Human/organisational hazards				
Human error	no	yes	no	yes
Safety culture aspects	no	yes	no	no
Assigning inadequate training for work steps	no	yes	no	yes
Assigning inadequate protective measures for work steps	no	yes	no	yes
External hazards / initiating events				
Ambient temperature extremes	-	no	-	no
Airplane crash	-	-	-	-
Storm and adverse weather conditions	-	no	-	no
Earthquakes	-	no	-	no
Flooding	-	no (site sufficiently high above sea level)	-	no
External explosions and fires	-	no (no buildings where such material is handled nearby)	-	no
Other Hazards	no	no	no	no
Degraded / corroded barriers, ageing of materials	no	no	no	no
Unknown or unmarked materials	no	no	no	no
Spills (due to decommissioning activities)	no	no	no	no
Malfunction of safety relevant systems (e.g. ventilation)	yes	yes	no	yes

The positive entries in this table have a different relevance for the safety assessment, ranging from situations or scenarios with minor consequences to those hazards which are limiting in the framework of the safety assessment for the research reactor. Therefore, the positive entries are discussed and put into perspective:

- Direct radiation sources: The radionuclide inventory mainly consists of radionuclides which contribute to external irradiation (^{60}Co, ^{137}Cs). External irradiation is the only relevant pathway during normal operation, if the personnel wear respiratory protection as needed during appropriate cutting operations or other work generating aerosols.
- Improper removal of shielding: Procedures for performing the decommissioning operation will always be carefully evaluated to ensure that large sources (contamination, activated structures, segmented highly active parts etc.) are always well shielded or that they are exposed only

shortly when being handled and that temporary shielding is provided as necessary. Improper removal of shielding is therefore generally dealt with in the operating procedures. Improper shielding conditions will, in addition, be readily detected by the health physics personnel during routine measurements.

- Radioactive material, incl. form: (solid, liquid, gaseous): In the present context, radioactive materials with relevance to the safety assessment mainly consist of the contamination present on inner surfaces in the form of dust. This issue has been taken into account when designing work safety issues, like prescription of wearing respiratory protection during those work steps where contamination could be mobilised and be suspended into the breathing air of personnel. Therefore, doses from inhalation are not taken into account for the analysis of the normal working conditions in this particular case, but inhalation in general is of relevance for safety assessments. For the analysis of accidents, however, it is conservatively assumed that inner contamination will accidentally be mobilised and that the worker being affected is not wearing respiratory protection equipment. In addition, the fact that some contamination which can be mobilised is present is also the reason for assuming any exposure of members of the public via airborne pathways during normal operating conditions.

- Flammable gases (e.g. oxyacetylene, propane gas), liquids, dust: The use of thermal cutting techniques could be an initiating event leading to a fire causing accidental activity release.

- Combustible / inflammable materials: During normal operation, such materials do not cause any hazard, as their quantity inside the research reactor is small and they are well controlled. They could contribute, however, to a fire causing accidental activity release.

- Overheating or fire, caused by e.g. portable heaters, overload of electrical circuits, application of cutting techniques: The application of certain cutting techniques may be the initiating event for a fire causing accidental activity release.

- Power overload and shortcuts, power failures: A power failure or a shortcut does not cause a hazard during normal operations, as the safety of operation does not depend on the continuous operation of any electrical powered device. If a crane lifting an unshielded source (an activated and contaminated item, a waste drum with high activity content that is to be put into a shielded cask) accidentally ceased operation due to a power failure so that the source remains unshielded, this could cause a hazard from external irradiation to the personnel. In such a case, however, the personnel will leave the area immediately and return only after power has been restored and the source can be lowered into its shielded container. Similar considerations are true e.g. for a malfunction of the ventilation.

- Inadequately disconnected circuits / prevention against inadvertent connection: This is taken into account for normal operation procedures. It does usually not form an initiating event for accidents.

- Asbestos and other hazardous materials, like lead or beryllium: Hazardous materials like asbestos from the insulation of pipes and cadmium are or may be present. Their position is usually well known to the personnel or is established during plant inspections prior to decommissioning, and the operating procedures take the presence of these materials into account. They are handled appropriately and do not pose an undue risk. The presence of these materials is not regarded as an initiating event for or forming part of any fault sequence leading to radiological consequences.

- Working at heights (e.g. ladders, scaffolding): Working at heights takes place to a limited extent but will be necessary during research reactor decommissioning. Scaffolds are e.g. used for working on or near the biological shield. Appropriate industrial safety measures have been put into place to avoid accidents. Therefore, this item is not regarded as relevant for analysis of accidental working conditions as it bears no radiological consequences. Working at heights is also not seen as an initiating event for a fault sequence leading to radiological consequences.
- Heavy lifts, material handling, heavy equipment, manual lifting, overhead hazards, falling objects, cranes: For normal operation, these hazards are duly covered by the operating procedures. For example, cranes may only be operated by skilled personnel, workers are forbidden to stay beneath lifted loads etc. These hazards are therefore not explicitly addressed in the hazard analysis for normal operation conditions. With respect to accident conditions, however, a drop of a waste container or a contaminated part of the research reactor which has been lifted may cause spread of contamination. Drop of loads is therefore included as an initiating event.
- Noise (high noise areas and tools): For some of the dismantling steps, tools creating high noise levels are used. Protective measures during normal operation have been taken (hearing protection). Noise is not regarded as an initiating event for or forming part of any fault sequence leading to radiological consequences.
- Dust: Larger amounts of dust can be created mainly during concrete demolition. Protective measures during normal operation have been put into place (respiratory protection). Dust is not regarded as an initiating event for or forming part of any fault sequence leading to radiological consequences.
- Pinch points, sharp objects: These may occur mainly during cutting operations. Normal industrial safety procedures are in place to prevent injuries. Pinch points or sharp objects are not regarded as forming part of any fault sequence leading to radiological consequences.
- Confined space: The only confined space of relevance for the safety assessments carried out here is the heavy water room. During normal operation, working in this area does not present any particular hazard. For the analysis of accident conditions, however, this area is chosen as the place where loose contamination could become mobilised, leading to doses from inhalation to a worker present in this area. Working in this confined space is, therefore, not the cause for an accident scenario (i.e. does not form an initiating event), but contributes to such a scenario.
- Dangerous equipment, e.g. power tools, compressed gas cylinders, welding and cutting, water jet cutting / decontamination, abrasive decontamination techniques, grinding, sawing: During normal operation, such techniques are applied only be skilled personnel. It is thus ensured that they do not pose a risk to the personnel during normal operation. Application of thermal cutting techniques may in principle be the cause for a fire and is therefore considered an initiating event.
- Airplane crash: An airplane crash is not a design base accident for the research reactor. It is therefore not included in the accident scenarios analysed for workers or members of the general public.

5.3 Calculation of doses to members of the public due to airborne releases for normal decommissioning operation

As the description of the site and its surroundings in section 2.2 reveals, exposure from normal decommissioning operations to members of the public can only occur from airborne releases. There are no liquid releases from the decommissioning work as all water from wet segmenting techniques are collected and treated at the liquid waste treatment facility of the research establishment. In addition, the activity inventory of the research reactor in relation to the shielding provided by the biological shield and the building is so small that external exposure around the building is totally negligible.

The following 4 steps show how doses from airborne releases can be used for calculation of doses to people living in the neighbourhood of the site. First, the source term is defined, based on the potential releases from the segmenting activities for the heat exchanger, the fuel flask and the concrete of the biological shield. Then the dispersion in the environment is modelled, providing activity concentrations on the ground and in the air for various locations. Finally, doses from inhalation and external exposure from ground deposits as well as for secondary ingestion via radioecological pathways are calculated.

(Note that these estimates are only very rough estimates that will overestimate the real doses considerably. This is the reason why this approach leads to higher dose estimates than those provided by Risø in its own documentation of doses from releases).

1. Determination of the source term:

The following assumptions for the source term are made for releases from the three cases (heat exchanger, fuel flask and biological shield) together, based on the estimate of releases provided by Risø in section 3.4. Note that only the most relevant radionuclides H-3, Co-60, Eu-152 and Eu-154 have been included (with both Eu isotopes handled together). In addition, Sr-90 has been included as well with a small activity, although this nuclide has not been mentioned in the radiological characterisations up to now. It is included as an example for a radionuclide with a high dose coefficient for ingestion and inhalation that has a good solubility in water. It is commonly found in the contamination in nuclear installations.

Table 5.2 Estimate of the release rate

	^{3}H	^{90}Sr	^{60}Co	$^{152+154}$Eu	
Release rate	$1 \cdot 10^{12}$	$1 \cdot 10^{5}$	$1 \cdot 10^{9}$	$2 \cdot 10^{7}$	Bq/a
Release rate	$3 \cdot 10^{4}$	0.003	30	0.6	Bq/s

2. Modelling of the dispersion in the environment:

A model for the atmospheric dispersion of the radionuclides from the point of release into the direction of the houses next to the research establishment where the research reactor is located is taken from subsection 3.5 of IAEA Safety Report Series No. 19 [IAE 01]. The ground level air concentration can be calculated as follows:

$$C_A = \frac{P_p \cdot B \cdot Q_i}{u_a}$$

where:

C_A ground level air concentration at downwind distance x (Bq/m³),
P_p fraction of the time the wind blows towards the receptor of interest,
B dispersion factor with building wake correction (1/m²)
Q_i average discharge rate for radionuclide i (Bq/s)
u_a geometric mean of the wind speed at the height of release representative of 1 m/s.

Taking the conservative assumption that the wind always blows into the direction of the nearest houses (P_p = 1), assuming an average wind speed of 1 m/s and using a factor B of $5 \cdot 10^{-4}$ m^{-2} corresponding to the geometrical conditions, the following air concentrations at the receptor point are calculated:

Table 5.3 Ground level concentration in air

	^{3}H	^{90}Sr	^{60}Co	$^{152+154}$Eu	
Ground level concentration in air, C_A	15	$2 \cdot 10^{-6}$	0.02	$3 \cdot 10^{-4}$	Bq/m³

The ground deposition of the radionuclides is calculated as follows:

$$\dot{d}_i = (V_d + V_w) \cdot C_A$$

where:
$\dot{d}_i$ total daily average deposition rate on the ground of a given radionuclide i from both dry and wet processes, including deposition either on impervious surfaces or on both vegetation and soil ($Bq \cdot m^{-2} \cdot d^{-1}$);
V_d dry deposition coefficient for a given radionuclide (m/d);
V_w wet deposition coefficient for a given radionuclide (m/d).

A conservative estimate for the sum of both deposition coefficients is 1000 m/d for all radionuclides except H-3 and 10 m/d (or even 0) for H-3. Assuming the discharge process to effectively last for 100 d (operation time), the following ground surface concentration values are calculated:

Table 5.4 Ground surface concentration

	^{3}H	^{90}Sr	^{60}Co	^{154}Eu	
Ground surface concentration	1,5E+04	0,2	1,5E+03	30	Bq/m²

3. Modelling of inhalation and external exposure from ground deposits:

The doses from inhalation are calculated as the product of breathing rate, exposure time, inhalation dose coefficient and radionuclide concentration in the air. Using an exposure time of an entire year

(8760 h/a), an average breathing rate for adults of 0.95 m³/h and for infants (0-1 a) of 0.16 m³/h, the following doses are calculated:

Table 5.5 Dose coefficients for inhalation

	^{3}H	^{90}Sr	^{60}Co	^{154}Eu	
Dose coefficient inhalation, adults	6,20E-12	1,60E-07	3,10E-08	5,30E-08	Sv/Bq
Dose from inhalation, adults	8,2E-07	2,1E-09	4,1E-06	1,4E-07	Sv/a
Dose coefficient inhalation, infants (0-1 a)	2,60E-11	4,20E-07	9,20E-08	1,60E-07	Sv/Bq
Dose from inhalation, infants (0-1 a)	5,8E-07	9,3E-10	2,0E-06	7,1E-08	Sv/a

The resulting effective doses from inhalation are thus about 4 µSv/a for adults and 3 µSv/a for infants from all four nuclides together.

The doses from external irradiation from the activity deposited on the ground is calculated as the product of the ground surface concentration values and the dose coefficients for surface deposits and the occupancy factor. While the dose coefficients for surface deposits is related to external irradiation during a whole year, the occupancy factor corrects for staying outside the house on the premises. It is set to 0.1, meaning that a person will stay about 1000 h/a outside the house.

This results in the following data:

Table 5.6 Dose due to external exposure due to ground deposit

	^{3}H	^{90}Sr	^{60}Co	^{154}Eu	
Dose coefficient for ground deposit	0	3,5E-09	7,5E-08	3,8E-08	(Sv/a)/(Bq/m²)
Dose from ext. irradiation, ground deposit	0	5,5E-11	1,2E-05	1,2E-07	Sv/a

The resulting effective dose from external irradiation from ground deposits is thus about 10 µSv/a and is caused nearly exclusively by Co-60.

4. Modelling of the secondary ingestion via radioecological pathways:

For modelling secondary ingestion, only vegetable consumption is taken into account as the houses next to the research reactor only have gardens allowing production of vegetables but no cultivation of corn or rearing of cattle. The contamination of vegetation is calculated as follows:

$$C_{v,i,1} = \frac{\dot{d}_i \alpha \left[1 - \exp\left(-\lambda_{E_i^v} t_e\right)\right]}{\lambda_{E_i^v}}$$

where

$C_{v,i,1}$	is measured in Bq/kg fresh matter for vegetation consumed by humans
$\dot{d}_i$	total daily average deposition rate on the ground of a given radionuclide *i* from both dry and wet processes ($Bq \cdot m^{-2} \cdot d^{-1}$), see above
α	is the fraction of deposited activity intercepted by the edible portion of vegetation per unit mass (or mass interception factor, m²/kg) as the result of both wet and dry deposition processes; here 0.3 $m^2/kg_{wet\ weight}$
$\lambda_{E_i^v}$	is the effective rate constant for reduction of the activity concentration of radionuclide *i* from crops (d^{-1}), where $\lambda_{E_i^v} = \lambda_i + \lambda_w$
t_e	is the time period that crops are exposed to contamination during the growing season (d), here 60 d
λ_w	is the rate constant for reduction of the concentration of material deposited on the plant surfaces owing to processes other than radioactive decay (d^{-1}), here 0.05 d^{-1}
λ_i	is the rate constant for radioactive decay of radionuclide *i* (d^{-1}).

Using the deposition rate calculated above as well as the ingestion dose coefficients and a conservatively high ingestion rate of 50 kg/a vegetables and other crops grown in the own garden, the following data result:

Table 5.7 Internal exposure due to ingestion

	^{3}H	^{90}Sr	^{60}Co	^{154}Eu	
Activity concentration in vegetation	8,9E+02	9,0E-03	9,0E+01	1,8E+00	Bq/kg
Dose coeff. for ingestion	1,80E-11	2,80E-08	3,40E-09	2,00E-09	Sv/Bq
Dose from ingestion of 100 kg/a crops and vegetables	8,0E-07	1,3E-08	1,5E-05	1,8E-07	Sv/a

A total dose of about 20 µSv/a follows from this ingestion pathway, dominated by ^{60}Co.

The sum from all dose contributions is thus conservatively estimated to less than about 30 µSv/a.

5.4 Calculation of doses to members of the public from accident conditions

There are only a few accident scenarios during the decommissioning operations of a research reactor that may lead to a release of activity to such an extent that exposure of the public would be radiologically relevant. A screening analysis therefore needs to define a sufficiently conservative source term for the activity release and calculate doses on the basis of a simple and enveloping model for dispersion and exposure pathways. Suitable generic assumptions for such an approach are taken from IAEA Safety Reports Series 19 and the Procedure for Calculating Doses from Accident Scenarios according to Section 49 of the German Radiation Protection Ordinance.

1. Determination of the source term:

A fire in the reactor hall with subsequent release of part of the contamination into the environment can be regarded as an enveloping accident scenario for the decommissioning phase. For simplicity, it is assumed that the contamination consists only of Co-60 and that the release takes place through a hole in the roof of the building (which may have been caused by an explosion starting the fire), i.e. the normal release pathway through ventilation and stack is no longer active. It is assumed that 10^8 Bq of Co-60 are released in this event.

The fire is assumed to burn for 2 hours (7,200 s). The release rate of activity is assumed to be constant during this time. This leads to the following source term to be released into the environment:

- ^{60}Co: 10^8 Bq/7,200 s = $1.4 \cdot 10^4$ Bq/s

2. Modelling of the dispersion in the facility and in the environment:

The release of the contaminated air takes place over the roof. The heat content in the air from the fire leads to a buoyancy of the air plume, so that the effective height of release is larger than the roof top. The effective height is therefore assumed to be 50 m.

For the subsequent dose calculations, it is necessary to know the (maximum) activity concentration in the air (for doses from inhalation and from beta / gamma submersion) as well as the surface activity concentration on the ground (for doses from external gamma irradiation from the ground and secondary ingestion via various food pathways). For screening purposes, the short-term dispersion factors are taken from tables and the pathways are limited, while in a more sophisticated analysis the dispersion factors would be calculated yielding more realistic results and all pathways would be taken into account.

Short-term dispersion factors for gamma submersion are provided in tabulated form e. g. in [IAE 01], where they are listed for effective release heights of and diffusion categories. For screening calculations, the highest dispersion factor for an effective release height of 50 m and diffusion category E is used, which is χ = 0.04 s/m². This value refers to a wind speed of 1 m/s. The corresponding wind speed in a height of z = 50 m can be estimated as 1.8 m/s. The effective dispersion factor for gamma submersion therefore becomes (0.04 / 1.8) s/m² = 0.022 s/m².

The short-term dispersion factor relevant for calculation of doses from inhalation, gamma depletion etc can be calculated as follows:

$$\hat{\chi}_j = \frac{1}{\pi \cdot \sigma_{y,j}(x) \cdot \sigma_{z,j}(x) \cdot u} \cdot \exp\left(-\frac{H_e^2}{2 \cdot \sigma_{z,j}^2(x)}\right) \cdot \exp\left(-\frac{y^2}{2 \cdot \sigma_{y,j}^2(x)}\right)$$

where

H_e	:	effective height of emission, 50 m (see above)
u	:	wind speed in the effective height of emission, 1.8 m
x, y	:	coordinates of receptor point (here, y = 0)
σ_y, σ_z	:	diffusion parameters, in m (see below)

The diffusion parameters can be calculated using the following approach:

$$\sigma_y = p_y \cdot d^{q_y} \text{ and } \sigma_z = p_z \cdot d^{q_z}$$

where

d	:	distance to the receptor point, in m
p_y	:	coefficient, 0.801
p_z	:	coefficient, 0.264
q_y	:	exponent, 0.754
q_z	:	exponent, 0.774

This results in the following values for the diffusion parameters for a distance of 1000 m:

$$\sigma_y = 146\ \text{m},\ \ \sigma_z = 55\ \text{m}$$

Inserting these data and the coordinates (x,y) = (500 m, 0 m) into the equation for the short-term dispersion factor above yields

$$\chi = 1.4 \cdot 10^{-5}\ \text{s/m}^3$$

Fallout and washout factors are relevant for providing an estimate of the activity which is depleted on the ground. The fallout factor F is the product of the short-term dispersion factor and the deposition velocity v_g (default value $1.5 \cdot 10^{-3}$ m/s):

$$F = \chi \cdot v_g$$

The washout factor is based on a precipitation intensity of 5 mm/h and is calculated according to

$$\hat{W}_j = \frac{\Lambda}{\sqrt{2\pi} \cdot \sigma_{y,j}(x) \cdot u} \cdot \exp\left(-\frac{y^2}{2 \cdot \sigma_{y,j}^2(x)} \right)$$

where the parameters have the meaning given above and

Λ : washout coefficient, in 1/s.

Inserting the relevant data into the equations for the fallout and washout factors yields:

$$F = 2.2 \cdot 10^{-8}\ \text{m}^{-2} \text{ and } W = 3.8 \cdot 10^{-7}\ \text{m}^{-2}$$

3. Modelling of inhalation

The inhalation is calculated from the breathing rate, the airborne activity concentration and the inhalation dose coefficient:

$$H_{inh} = g_{inh,r} \cdot \dot{Q}_r \cdot t_{rel} \cdot \chi \cdot \dot{V}$$

where

t_{rel} : duration of the release
$g_{inh,r}$: inhalation dose coefficient for nuclide r
$\dot{Q}_r$: release rate for nuclide r
$\dot{V}$: breathing rate, 1.2 m³/h
g_{inh} : $3.1 \cdot 10^{-8}$ Sv/Bq for Co-60

Inserting these data into the equation for the inhalation dose above yields $2 \cdot 10^{-8}$ Sv for Co-60.

4. Modelling of external exposure from ground deposition and from submersion:

The dose from external irradiation of radionuclides depleted on the ground can be calculated as follows, describing the dose for an adult as the follow-up dose until the age of 70 years (i.e. to cover the lifetime between the age of 18 and 70).

$$H_T = \left[(1-\vartheta) \cdot g_{b,r}^{>17a} + \left(1-\vartheta^{52}\right) \cdot b \cdot g_{b,r}^{>17a} \right] \cdot \frac{1}{\lambda_r} \cdot (F + W) \cdot \dot{Q}_r \cdot t_{rel}$$

with the abbreviation $\vartheta = \exp(-\lambda_r \cdot t_1)$

where

t_1	:	duration of 1 year
λ_r	:	decay constant, $4.2 \cdot 10^{-9}$ s^{-1} for Co-60
$g_{b,r}^{>17a}$	:	dose coefficient for external irradiation from ground deposit for adults (> 17 a), $2.4 \cdot 10^{-15}$ (Sv/s)/(Bq/m²) for Co-60

Inserting these data into the equation for the doses from external irradiation from ground deposits above yields $1 \cdot 10^{-5}$ Sv for Co-60.

The dose from external irradiation from the immersion in the cloud at ground level can be calculated, using a simplified approach, as follows:

$$H_\lambda = g_{\gamma,r} \cdot \dot{Q}_r \cdot t_{rel} \cdot \chi_\gamma$$

where

$g_{\gamma,r}$	:	dose coefficient for external irradiation from immersion in the cloud, $1.3 \cdot 10^{-13}$ (Sv/s)/(Bq/m³) for Co-60

Inserting these data into the equation for the doses from external irradiation from immersion above yields $3 \cdot 10^{-7}$ Sv (0.3 µSv) for Co-60.

5. Calculation of the total dose:

The total dose from the scenarios included here is calculated as the sum from the above three scenarios. This yields 20 µSv for Co-60.

6. Limitations of the preliminary analysis

This coarse analysis relies on the following simplifications:

- The distance is set to 1000 m as this roughly corresponds to the position of the family homes to the east of the research reactor site. The analysis has also to be done for shorter distances with properly adjusted conditions (no dwellings).

- The dispersion has been calculated only for diffusion category E, i.e. stable conditions, which is a generally conservative assumption but does not guarantee to hit the maximum.

- The analysis has been done only for adults and needs to be worked out for other age groups as well.

- The analysis did not take into account ingestion of food grown on the contaminated land. These pathways would have to be included in a more refined analysis. It is nevertheless justified to exclude these more complicated pathways in this first screening analysis as the ingestion pathways constitute medium and long term effects and might in principle be ruled out by appropriate administrative measures (prohibition of harvesting crops etc.).

6. SOLUTIONS

This section provides solutions for the questions posed in section 4, using the elements for safety assessments provided in section 5.

6.1 Solutions for Case 1

This section provides solutions for the questions to Case 1 – dismantling of a heat exchanger:

1. *Normal operation, workers:*

   a) *What are the risks to the workers and the associated potential exposure pathways during normal operation? Please provide a list of hazards that you think might be relevant. Which are the most important ones? Why?*

The most relevant radiological risks are external exposure and inhalation during use of thermal cutting techniques or other techniques that give rise to aerosols. Inhalation of H-3 should be monitored but should not be a problem. In addition, there are conventional risks that are also encountered during similar conventional cutting operations. The list provided in section 5.2 can be used for identification of potential risks.

The radiological risks external exposure and inhalation are those that need to be considered in the following. However, it will be required that workers wear protective equipment during use of segmenting tools (respiratory protection) that will hold back at least 99 % of the airborne activity. This means that for normal operation doses from inhalation need not be considered.

   b) *Consider the two options for segmenting of the heat exchanger: mechanical cutting techniques (in particular sawing, rather slow, no aerosols) and thermal cutting techniques (in particular plasma arc cutting, fast, large amount of aerosols). Structure the work into reasonable work packages for both options. Identify situations that can be regarded as bounding for each work package (neglect the transport of the heat exchanger from the heavy water room to the segmenting area). Prepare scenarios describing the possible exposure situations for these situations, in particular taking account of the inhalation pathway and protective measures against inhalation and of the significant differences in exposure time. How would you calculate the doses to the personnel in each case?*

Work packages for dismantling of the heat exchanger could be the following:

- Segmenting the pipes from the heat exchanger so that it later can be removed.
- Removal of any parts that are obstructing the later removal of the heat exchanger.
- Installation of a crane to which the heat exchanger can be attached.
- Unfixing the heat exchanger from its current position and attaching it to the lifting equipment.
- Moving the heat exchanger outside the heavy water room and tilting it to a horizontal position (if necessary with a support).
- Moving the heat exchanger to the hacksaw by which it will be further segmented.
- Sawing the heat exchanger into segments.
- Further segmenting the rings of the heat exchanger.

- Later steps might comprise decontamination, clearance, packaging as radioactive waste etc. These steps, however, are not further considered here.

A bounding scenario obviously can be represented by working in close vicinity of the item. It can be assumed that the same group of workers will carry out all the work steps (or at least that there is one person participating in all work steps). The amount of time that can be calculated for all work steps is assumed as 1 month or about 200 h. It can be assumed that the workers will work only about 50 % of the time inside the heavy water room and the rest of the time in an area where the segmenting etc. is prepared, maintenance for tools is carried out etc.

The average dose rate can be estimated from the data provided in Table 3.2 as about 10 to 20 µSv/h, both from the components in the heavy water room and from the heat exchanger itself. The dose rate in the other area can be conservatively estimated as 1 µSv/h.

c) *Perform the dose calculations and give a bounding estimate for the doses that workers may receive for both options. The result can be regarded as a bounding estimate of the doses to workers during the planned work.*

A bounding estimate for the dose that a worker will receive during dismantling of the heat exchanger could be simply calculated as the sum of the products of the exposure times and the corresponding dose rates. Using the above assumptions, the dose would be $100\ h \cdot 15\ \mu Sv/a + 100\ h \cdot 1\ \mu Sv/a = 1.6\ mSv$. As stated above, inhalation can safely be excluded as protective measures will be used.

d) *Which of the two options for dismantling of a heat exchanger (thermal or mechanical cutting techniques) is the best one from a radiological point of view? – Consider only this technique for the subsequent questions.*

A thermal cutting technique that would be well applicable to the removal of the heat exchanger would be plasma arc cutting. This technique will give rise to about $1\ Bq/m^3$ per $1\ Bq/cm^2$ for this type of cutting operation.

Suitable mechanical cutting techniques would be sawing or milling. These techniques will produce only small particles (chips) that can easily be collected and will not produce any aerosols. The activity of these particles simply corresponds to the activity of the base material.

Comparison of the two types of cutting techniques first requires analysis the objective to be achieved.

- Objective: minimisation of working time. This could be achieved by using fast thermal cutting technique, which, however, requires an enclosure with separate ventilation and filtration. If faster thermal cutting techniques are used, the time required for erection of this enclosure and for setting up the ventilation also need to be taken into account. This reduces the advantage gained by applying a faster cutting technique to a certain degree, but there still should be an overall gain in time. There should, however, be an overall advantage for thermal techniques.

- Objective: no aerosols, minimisation of contamination spread. This could be achieved by using (slower) mechanical cutting techniques.

2. *Incidents or accidents, workers:*

a) *What incidents or accidents (with radiological consequences) could happen to workers during the work, taking also the confined space in the heavy water room and the use of thermal cutting techniques in the tent into consideration? How would you rank their probability for occurrence? Consider external exposure, inhalation of dust and aerosols.*

b) *Which exposure scenarios could be used in each case? Can you identify bounding scenarios? Which exposure pathways have to be taken into account?*

There are various possible accident scenarios with radiological consequences. An enveloping scenario is that a person is injured in the room and has to take off respiratory protection in order to facilitate breathing etc. while the room is filled with airborne contamination, In addition, the time required to fetch a stretcher and a second person trained in first aid or a doctor being able to decide whether the injured person can be moved and the time required for examination may be assumed to be 15 min. The aerosol concentration can be assumed to be 1,000 Bq/m³ (see section 3.5) if metal with surfaces with higher contamination have been cut.

Other accident scenarios might be exposure to a source, e.g. by erroneous removal of shielding for a certain time, e.g. 1 h.

c) *Perform the dose calculations for these bounding scenarios. Which scenario leads to the highest dose?*

The dose calculation can be performed by simple multiplication of the airborne activity concentration, the breathing rate (about 1 m³/h), the time (0.25 h) and the inhalation dose coefficient (for Co-60: $3.1 \cdot 10^{-8}$ Sv/Bq). The result would be about 10 µSv.

3. *Normal operation, public:*

a) *Which are potential exposure pathways by which the general public could be exposed? Take into account external exposure, inhalation of aerosols / dust, direct ingestion and secondary ingestion pathways.*

The normal operation will cause airborne releases from which the public, i.e. people living to the east of the Risø site and producing part of their diet from cultivation in their own gardens or farmland. A suitable scenario along with an enveloping source term for annual decommissioning operations has been described in section 5.3.

b) *Give an estimate for the source terms relevant to these exposure pathways.*

An estimate for a source term from the overall decommissioning operations in DR3 (i.e. not only those for cutting the heat exchanger) has been given in section 5.3.

c) *Provide a very simple estimate of the dose to a person of the general public on the basis of the identified exposure pathways and the source term (upper bound). Is it necessary to perform an in-depth analysis of the exposure to the public? Why?*

A dose estimate has been provided in section 5.3. The result of about 30 µSv/a shows that the doses are not entirely negligible and need at least be discussed. It also shows that a more in-depth analysis would not be necessary.

4. *Incidents or accidents, public:*

a) *Consider a situation where accidentally an internal contamination inside the heat exchanger that has not been noted previously is released to the plant atmosphere and from there to the environment because the filter is not working for some reason. What would be a suitable assumption for a source term?*

The assumption of a fire usually provides an enveloping case for an accident scenario. As in the case of a fire, the ventilation would be shut down and the reactor hall would thus be sealed, it can further be assumed conservatively that an explosion (which may have started the fire) will create a hole in the wall or the roof where the activity is released directly. The source term can only be estimated roughly, but the assumption of a release of 10^8 Bq as in section 5.4 would certainly be enveloping. Other radionuclides might be present but to a minor degree.

b) *Perform a simple calculation of doses to the public for this scenario assuming unfavourable meteorological conditions (i.e. conditions leading to a high exposure).*

This calculation is shown in section 5.4. The result of the calculations is less than 1 μSv (for this event).

5. *Summary*

a) *Provide a summary of the results under points 1 to 4 indicating the overall assessment of safety for the envisaged work.*

A summary of this analysis could be as follows: The envisaged decommissioning work for the removal of a heat exchanger will lead to individual doses for the workers that are on the order of 1 to 2 mSv. Accidents during work will not lead to very high doses even if no respiratory protection could be worn for some time. The doses to the public from normal decommissioning operation are not negligible, but far below any dose constraints or limits. The doses to the public from enveloping accident scenarios are very small.

Relevant SSCs and safety measures: For workers, respiratory protection has been identified as necessary for any work on contaminated structures where airborne releases are created. Continued operation of the ventilation of the reactor building is also necessary. For mitigating releases to the environment and as a consequence exposure of the public, continued operation of the HEPA-filters for the exhaust air and its discharge through the ventilation stack is relevant.

6.2 Solutions for Case 2

This section provides solutions for the questions to Case 2 – dismantling of the fuel flask.

1. *Normal operation, workers:*

a) *What are the risks to the workers and the associated potential exposure pathways during normal operation? Please provide a list of hazards that you think might be relevant. Which are the most important ones? Why?*

See answer to Case 1.

b) *Consider the two options for segmenting of the fuel flask: mechanical cutting techniques (in particular sawing, rather slow, no aerosols) and thermal cutting techniques (in particular plasma arc cutting, fast, large amount of aerosols). Structure the work into reasonable work packages for both options. Identify situations that can be regarded as* *bounding for each work package. Prepare scenarios describing the possible exposure situations for these situations, in particular taking account of the inhalation pathway and protective measures against inhalation and of the significant differences in exposure time. How would you calculate the doses to the personnel in each case?*

A suitable work sequence could be:

- Tilting fuel flask will into a horizontal position (note that Figure 3.3 shows the flask in its vertical working position). If necessary, construction of a support.
- Removal of parts that can be dismantled easily from the outside of the flask. While the outer contamination is negligible, the contamination on the interior surface requires decontamination or at least techniques for avoiding its spreading during segmenting. Segmenting of the component is therefore carried out in a temporarily erected tent which is connected to a ventilation and filtration device.
- First, segmentation of the hollow part of the flask into ring segments (annular cylinders) of appropriate thickness that can be easily handled.
- Further segmentation of these segments further into pieces appropriate for radioactive waste storage or clearance.
- Finally, cutting of the top part by horizontal cuts.

c) *Perform the dose calculations and give a bounding estimate for the doses that workers may receive for both options. The result can be regarded as a bounding estimate of the doses to workers during the planned work.*

As a first estimate, the working time may be assumed to be 1 month with 50 % of this time actual cutting and removal operation near the device. According to section 3.2.1, dose rate is small at the outside, but with progress of cutting interior parts will lead to exposure. Thus, an average dose rate of 20 µSv/h could be assumed. This will lead to the same dose estimated as for Case 1.

d) *Which of the options for segmenting of the fuel flask (mechanical or thermal) is the best one from a radiological point of view? – Consider only this technique for the subsequent questions.*

See answer to Case 1.

2. *Incidents or accidents, workers:*

a) *What incidents or accidents could happen to workers during the work, taking the weight of the component and the need for supporting pieces that have been cut into account? How would you rank their probability for occurrence? Consider external exposure and inhalation of aerosols.*

If thermal cutting techniques in combination with an enclosure (tent) are used, a similar accident scenario could happen as described for the heavy water room above, i.e. a small enclosure could be filled with aerosols, the accident happens to a worker inside the tent who has to take off the respiratory protection for facilitating breathing, and it might take some time until is can be decided whether it is safe to move the person. This would lead to similar doses as calculated for Case 1.

Note that in reality there are many ways to instantaneously reduce the doses, e.g. by deciding to cut the tent immediately open, thus reducing exposure, to fetch a breathing apparatus etc.

b) *Which exposure scenarios could be used in each case? Can you identify bounding scenarios? Which exposure pathways have to be taken into account?*

The answers are similar to those provided for Case 1.

c) *Perform the dose calculation for these bounding scenarios. Which scenario leads to the highest dose?*

The answers are similar to those provided for Case 1.

3. *Normal operation, public:*

a) *Which are potential exposure pathways by which the general public could be exposed? Take into account external exposure, inhalation of aerosols / dust, direct ingestion and secondary ingestion pathways.*

b) *Give an estimate for the source terms relevant to these exposure pathways.*

c) *Provide a very simple estimate of the dose to a person of the general public on the basis of the identified exposure pathways and the source term (upper bound). Is it necessary to perform an in-depth analysis of the exposure to the public? Why?*

The calculation is entirely similar to the one in Case 1, as the assumption on released activities was made bounding for all 3 cases.

4. *Incidents or accidents, public:*

a) *Consider a situation where accidentally an internal contamination inside the fuel flask that has not been noted previously is released to the plant atmosphere and from there to the environment because the filter is not working for some reason. What would be a suitable assumption for a source term?*

b) *Perform a simple calculation of doses to the public for this scenario assuming unfavourable meteorological conditions (i.e. conditions leading to a high exposure).*

The calculation is entirely similar to the one in Case 1, as the assumption on released activities was made bounding for all 3 cases.

5. *Summary*

a) *Provide a summary of the results under points 1 to 4 indicating the overall assessment of safety for the envisaged work.*

A summary of this analysis could be as follows: The envisaged decommissioning work for the segmentation of the fuel flask will lead to individual doses for the workers that are on the order of 1 to 2 mSv. Accidents during work will not lead to very high doses even if no respiratory protection could be worn for some time. The doses to the public from normal decommissioning operation are not negligible, but far below any dose constraints or limits. The doses to the public from enveloping accident scenarios are very small.

Relevant SSCs and safety measures: For workers, respiratory protection has been identified as necessary for any work on contaminated structures where airborne releases are created. Ventilation of the area where segmenting of the fuel flask takes place (the reactor building or the active workshop) is also necessary. For mitigating releases to the environment and as a consequence exposure of the public, continued operation of the HEPA-filters for the exhaust air and its discharge through the ventilation stack is relevant.

6.3 Solutions for Case 3

This section provides solutions for the questions to Case 3 – demolition of the biological shield.

1. *Normal operation, workers:*

   a) *What are the risks to the workers and the associated potential exposure pathways during normal operation? Please provide a list of hazards that you think might be relevant. Which are the most important ones? Why?*

   The relevant risks to workers originate from external irradiation and inhalation of dust from the cutting operation. Furthermore, heavy blocks (in the case of diamond wire cutting) or heavy containers with building rubble (in the case of demolition with a pneumatic chisel) will be lifted, and part of the work has to take place on scaffolds. Therefore, risks from lifting of loads and working in heights are relevant, too.

   b) *Consider the three options for demolition of the biological shield (wet and dry diamond wire cutting and hydraulic shovel with a pneumatic chisel). Structure the work into reasonable work packages for the three options. Identify situations that can be regarded as bounding for each work package. Prepare scenarios describing the possible exposure situations for these situations. How would you calculate the doses to the personnel in each case? Make an estimate of the activity and its spatial distribution from the data reported in section 3.3.1. Estimate the dose distribution around the biological shield from these activity data.*

   Wet and dry diamond wire cutting lead to blocks that can be moved by the crane and can be taken out of the reactor for further segmenting ex situ (if necessary) to remove the parts that will be radioactive waste or for disposal on a normal landfill site after clearance. Using a hydraulic shovel with a pneumatic chisel will pulverise the entire concrete block and thus create a large amount of dust. This means that the aerosol generation will be minimised if diamond wire cutting is used. Experience shows that this is also the overall faster method, if the blocks can be sufficiently large and therefore the number of cuts be minimised.

   The choice between wet and dry diamond wire cutting is usually driven by the fact whether treatment facilities for contaminated water are available. Wet cutting processes use water or a lubricant solvent for reducing the wear of the wire and for cooling purposes. Dust from cutting is taken up by the water / solvent giving rise to sludge that has to be treated. Dry cutting processes are available with similar durability of the wires. In this case, however, the costs for the wires are higher and the dusts from cutting operation have to be removed by suction devices at the point where the wire leaves the kerf.

   The dose calculation depends on the technique: exposure time, distances, aerosol concentration. For work taking place in the vicinity of the concrete, the dose rate can be conservatively assumed to be on the order of several 10 µSv/h. The required time will depend strongly on the size of the concrete blocks that can be handled, which in turn determines the required overall cutting length (or more precisely: cutting surface) and thus the time. In total, cutting operation will require at least one month, so that a bounding estimate for working in the vicinity of the biological shield could be 2 months. In addition, aerosols have to be considered which might be taken into account by a small contribution to doses by inhalation. A suitable activity concentration could be derived from the cutting speed (e.g. 0.5 m^2/h, thickness of the wire about 10 mm, i.e. kerf volume 0.005 m^3/h, dust generation about 5 g/s, 1 % becoming airborne and inhalable, distribution of this dust into a volume of 10 m³, leading to a dust load of 5 mg/m³; using a specific activity of 100 Bq/g, this corresponds to an activity concentration of about 1 Bq/m³). The dose from inhalation is thus negligible.

c) *Perform the dose calculations and give a bounding estimate for the doses that workers may receive for all three options. The result can be regarded as a bounding estimate of the doses to workers during the planned work.*

The dose calculation leads to similar results as in Case 1 or Case 2.

d) *Which of the three options for demolition of the biological shield (wet and dry diamond wire cutting and hydraulic shovel with a pneumatic chisel) is the best one from a radiological point of view? – Consider only this technique for the subsequent questions.*

The dose calculation can be performed as shown above for Case 1 and Case 2. It is mainly influenced by the overall cutting time, so that the diamond wire cutting is preferable. In addition, handling of sludge and water from cutting will cause additional exposure, making dry diamond wire cutting the best option. In this case, the dust would be already packed into a 200 l drum that can be affixed to the ventilation and filtration device that is used for removal of dust.

2. *Incidents or accidents, workers:*

a) *What incidents or accidents could happen to workers during the work? How would you rank their probability for occurrence? Consider external exposure, inhalation of dust and skin contamination.*

Accidents might happen e.g. because of rupture of the diamond wire, dropping of loads etc. A scenario leading to a high aerosol concentration would be dropping of a waste drum filled with dust from dry diamond wire cutting, injuring a worker who would have to stay in the area for some time until being rescued. The calculation is similar to Case 1 and Case 2.

A short analysis shows that skin doses are negligible.

b) *Which exposure scenarios could be used in each case? Can you identify bounding scenarios? Which exposure pathways have to be taken into account?*

See Case 1 and Case 2.

c) *Perform the dose calculation for these bounding scenarios. Which scenario leads to the highest dose?*

See Case 1 and Case 2.

3. *Normal operation, public:*

a) *Which are potential exposure pathways by which the general public could be exposed? Take into account external exposure, inhalation of aerosols / dust, direct ingestion and secondary ingestion pathways.*

b) *Give an estimate for the source terms relevant to these exposure pathways. In particular, consider the H-3 content of the concrete.*

c) *Provide a very simple estimate of the dose to a person of the general public on the basis of the identified exposure pathways and the source term (upper bound). Is it necessary to perform an in-depth analysis of the exposure to the public? Why?*

The calculation is entirely similar to the one in Case 1, as the assumption on released activities was made bounding for all 3 cases.

4. *Incidents or accidents, public:*

   a) *Consider a situation where accidentally a large amount of contaminated dust is created which is then partly released to the environment because the filter gets clogged and loses its function. What would be a suitable assumption for a source term?*

   b) *Perform a simple calculation of doses to the public for this scenario assuming unfavourable meteorological conditions (i.e. conditions leading to a high exposure).*

   The calculation is entirely similar to the one in Case 1, as the assumption on released activities was made bounding for all 3 cases.

5. *Summary*

   a) *Provide a summary of the results under points 1 to 4 indicating the overall assessment of safety for the envisaged work.*

A summary of this analysis could be as follows: The envisaged decommissioning work for segmenting of the biological shield will lead to individual doses for the workers that are on the order of a few mSv. Accidents during work will not lead to very high doses even if no respiratory protection could be worn for some time. The doses to the public from normal decommissioning operation are not negligible, but far below any dose constraints or limits. The doses to the public from enveloping accident scenarios are very small.

Relevant SSCs and safety measures: For workers, respiratory protection has been identified as necessary for any work on activated and/or contaminated structures where airborne releases are created. Continued operation of the ventilation of the reactor building is also necessary. For mitigating releases to the environment and as a consequence exposure of the public, continued operation of the HEPA-filters for the exhaust air and its discharge through the ventilation stack is relevant.

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