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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

Abstract

This report presents a feasibility study of a melting facility for core components and reactor internals. An overview is given of how such a facility for treatment of intermediate level waste might be designed, constructed and operated and highlights both the possibilities and challenges.

A cost estimate and a risk analysis are presented in order to make a conclusion of the technical feasibility of such a facility. Based on the authors' experience in operating a low level waste melting facility, their conclusion is that without technical improvements such a facility is not feasible today. This is based on the cost of constructing and operating such a facility, in conjunction with the radiological risks associated with operation and the uncertain benefits to disposal and long term safety.

Contents

Definitions

Low level waste	Waste that when packaged has a surface dose rate < 2 mSv/h. This also applies for the unshielded material.
Intermediate level waste	Waste that when packaged has a surface dose rate between 2 and 500 mSv/h.
High level waste	Waste generating heat > 2 kW/m^3.
Short-lived waste	Waste with a non-significant inventory of nuclides with half-lives above 31 years.
Long-lived waste	Waste with a significant inventory of nuclides with half-lives above 31 years.
Core components	Components close to the reactor core that are neutron activated to a large degree. Approximately up to 0.5 meter distance from the core.
Reactor internals	Components that are further from the core and therefore are mainly surface contaminated rather than activated.

Abbreviations

ALARA	As Low As Reasonably Achievable
ATB	Waste Transport Container
BAT	Best Available Technology
BWR	Boiling Water Reactor
HLW	High Level Waste
HTO	Humans-Technologies-Organization
ILW	Intermediate Level Waste
LL	Long-Lived
LILW	Low and Intermediate Level Waste
LLW	Low Level Waste
NPP	Nuclear Power Plant
PWR	Pressurized Water Reactor
RPV	Reactor Pressure Vessel
SFR	Final Repository for Short-lived Radioactive Waste
SFL	Final Repository for Long-lived Radioactive Waste
SKB	Svensk Kärnbränslehantering AB, The Swedish Nuclear Fuel and Waste Management Company
SL	Short-Lived
SSM	Strålsäkerhetsmyndigheten, The Swedish Radiation Safety Authority
WAC	Waste Acceptance Criteria

1 Background

The Swedish Nuclear Fuel and Waste Management Company (SKB), has been assigned the task of handling and disposal of all types of radioactive waste including spent nuclear fuel in a safe way.

The radioactive waste from the Swedish nuclear industry is categorized into three major groups:

- Short-lived low and intermediate level waste (SL-LILW).
- Long-lived low and intermediate level waste (LL-LILW).
- High level waste – HLW (spent nuclear fuel).

Long-lived radioactive waste is defined as waste with a significant content of nuclides with a half-life greater than 31 years. However, long-lived radioactive waste also contains short-lived nuclides and for waste from nuclear power plants (NPPs), the short-lived nuclides are totally dominating in an external dose perspective.

In 2011 SKB started an R&D programme for evaluating different disposal concepts for LL-LILW. The purpose was to develop alternative repository concepts and conditioning methods for LL-LILW and to evaluate and compare them from a range of parameters. The goal is to present a comparison between identified repository concepts by 2013. The material should be of such a quality that SKB can make decisions of which concepts that are to be further investigated in a safety analysis.

As a part of the R&D programme for the LL-LILW disposal facility, Studsvik was assigned to investigate whether melting of metallic LL-LILW is technically feasible and, if so, what the requirements are to build and operate such a facility.

Specific concern was given to the following metallic components:

- Core components and reactor internals from both boiling water reactors (BWRs) and pressurized water reactors (PWRs).
- Reactor pressure vessels from PWRs.

1.1 Objective

The objective of this study is to find out whether melting and casting of metallic LL-LILW is a feasible process and what the implications of operating such a facility are on safety and economics of the disposal system.

1.2 Purpose and content of the report

The purpose of this report is to describe how a melting facility for LL-LILW might function, and to evaluate it from a safety and economical point of view.

The report covers the following areas:

- Equipment needed for handling, lifting and melting.
- Radiation protection.
- Process flows, logistics.
- Worker protection.
- Personal safety during construction and operation.
- Discharge to recipient.
- Energy consumption during operation.
- Cost for the design, construction and operation of the facility.

The report also includes details concerning identified limitations and problem areas for this method as well as an evaluation of the technical maturity of such a facility as a whole and for the technical equipment. The report also includes assessments of the extent to which the development of new equipment will be required and in what areas it is deemed most critical.

1.3 Special notes

There is no difference between the treatment of radioactive waste classified as short-lived or long-lived if the dose rates are equal, since only the short-lived nuclides have any impact on the handling and safety precautions.

Furthermore, since a few decades there are processing facilities in operation for low-level short-lived and long-lived metallic waste providing services on commercial basis. One of these facilities is located on the Studsvik site in Sweden.

2 Introduction

As Sweden is approaching decommissioning of its first commercial nuclear power plant, the management of radioactive scrap metal is becoming an increasingly important subject. There is a significant volume of metallic waste not suitable for free release or for disposal in the final repository for short-lived radioactive waste (SFR) due to its high content of long-lived nuclides.

This report discusses the feasibility of melting scrap metal with elevated dose rates. This treatment method is currently applied to LLW with the purpose of disposal volume reduction mainly by the large potential to treat such metal for free release. In cases where free release is not possible, melting usually offers a high degree of volume reduction for bulky objects. Furthermore, by binding activity in the waste matrix, a homogenized waste product is formed.

The ILW category poses several challenges which make melting of such waste problematic. In general, ILW cannot be treated for free release. For the same reason the dose rates from such waste are often high and require specific concern to factors such as personnel safety, environmental safety etc.

While it is not possible to treat ILW for free release, melting of such materials can possess other advantages, such as volume reduction, homogenization, delay of release etc.

In the following chapters many aspects of the benefits and problems with melting will be discussed and a conclusion as to whether such treatment is feasible or not is presented.

3 Objectives and limiting factors with melting

In this chapter, the objectives for melting of radioactive scrap metal are presented both in general and with special focus on metals with elevated levels of radioactivity. Limiting factors for melting, including handling and pre-treatment, are elaborated.

3.1 Benefits of melting

The benefits of melting radioactive waste depend to some degree on the waste category.

For LLW the main benefits are

- Transfer of volatile species, as well as alpha emitting nuclides, to secondary waste.
- Binding of the remaining radioactivity in the metal structure.
- High precision in the radioactivity determination by homogenisation of the entire melt batch. Samples will be representative for the batch.
- Potential for free release of material due to the above factors.
- Volume reduction.
- Reduction of surface-to-volume ratio.

For the ILW components discussed in this report, there is no potential for free release of material due to the high specific activities, parts of the reactor pressure vessel (RPV) being a possible exception. The main benefits are therefore the production of a homogeneous waste form with a reduced volume and a reduced surface-to-volume ratio.

3.1.1 Reduced surface to volume ratio

The main release mechanism of activity from activated metallic waste is through corrosion of the waste. In the corrosion process, nuclides previously bound in the matrix of the material are released and can be transported out of the repository to the biosphere. In the anaerobic corrosion process also large amounts of hydrogen gas which can have a detrimental impact on the engineered barrier system are formed.

For this reason, one of the main benefits of melting is the reduction of the accessible surface by the formation of homogeneous metallic ingots. This is schematically illustrated in Figure 3-1.

Therefore, by melting metallic waste and lowering the surface to volume ratio, the corrosion rate calculated as kg/year is reduced even though the corrosion rate in µm/year is not affected. This allows for longer decay time before the activity is released, and consequently to a reduced impact on the biosphere.

From a technical point of view this may potentially affect the need for technical barriers in the repository.

3.1.2 Reduced disposal volume

By melting, the total waste volume can be significantly reduced. Reduced volume has a number of advantages.

Figure 3-1. *Schematic illustration of surface to volume ratio reduction of a cuboid shape (2×20×100 cm) to a spherical shape (radius = 9.8 cm). Note that the volumes of the objects are the same while the spherical object has a smaller surface area.*

Reduction of the volume of produced waste consequently leads to a reduction in the needed capacity of disposal. This has economic benefits for the repository operator, which in turn is transferred to both the waste producer and its customers.

Furthermore, an increased packing efficiency will reduce the problem with void in the repository. This will reduce the need for other void-minimization techniques such as grouting.

3.1.3 Binding of activity in the metal structure

Another parameter of importance for the long term safety is the homogenisation of activity in the metal matrix. This is of particular importance for metal waste forms in which a significant fraction of the radioactivity is in the form of surface contamination.

Binding surface contamination to the matrix of the material also reduces the potential release and contamination, both during handling and in the long term (see also Section 3.1.1). From a dose rate perspective such homogenisation also takes advantage of the self-shielding of the metallic structure, reducing the need for shielding in the packaging.

3.2 Limiting factors

While there are several benefits from a long-term safety perspective of melting LL-ILW, there are several limiting factors, mainly related to the operational safety of such a facility.

3.2.1 Dose burden

Due to the high dose rate in LL-ILW the dose burden to personnel involved in the handling, transport and treatment of such material is of significant concern.

From the waste producers' perspective, the handling and transport of LL-ILW is a well-known and challenging task. This type of material is often segmented by the use of remotely controlled equipment in shielded areas such as hot-cells or pools. The waste is then transported using containers with an adequate shielding.

The operation of a melting facility for LL-ILW waste introduces further complications. From a dose burden perspective, the use of remotely controlled equipment is required in all steps from pre-treatment to final packaging.

The main limiting factor is the melting process itself. As discussed further in following chapters, operating a furnace for radioactive waste is complicated, with several risks involved. Operational disturbances are not uncommon, and mitigation of the potential consequences is likely to involve the need to use non-remote techniques, Section 7.4. This limits the allowable radioactive content in the furnace and therefore the potential to melt certain waste types.

3.2.2 Release of activity during treatment

Some nuclides are volatile and cannot be contained in the melt. Instead they escape to the off-gas treatment system and to some extent also to the surrounding environment. The most problematic nuclides are ^{14}C, ^{3}H and some other volatiles. The latter can be filtered to a large degree, while ^{14}C is much more difficult.

The dose burden to a member of the critical group from radioactive release is qualitatively discussed in Chapter 8.

Furthermore, the release during a potential accident must also be taken into account due to the inherent risks in a melting facility.

3.3 Radioactive waste melting facilities currently in operation

Studsvik melting facility

The existing melting facility at Studsvik processes radioactive metallic scrap metal. Most material delivered for treatment has an activity level of a few Bq/g of gamma emitting nuclides. Materials with up to 100 Bq/g of gamma emitting nuclides can be accepted for treatment on a case by case basis. Materials with an estimated activity level above the clearance level are decontaminated prior to melting.

The main purpose of the treatment is to qualify the metal for free release after treatment. For material with a higher activity content melting is performed for volume reduction purposes.

The facility is currently licensed for 5,000 tonnes/year. The melting capacity is 9,000 tonnes/year but the pre-treatment capacity is significantly lower.

Due to the low dose rates, conventional hands-on techniques can be used in most cases. For some of the material to be melted, segmentation and decontamination have to be conducted in a closed area.

Shielding is applied where found necessary. Also with relatively low dose rates, shielding is applied in accordance with the ALARA principle.

Other melting facilities in operation

Other melting facilities for radioactive waste in Europe are presented in Table 3-1 below.

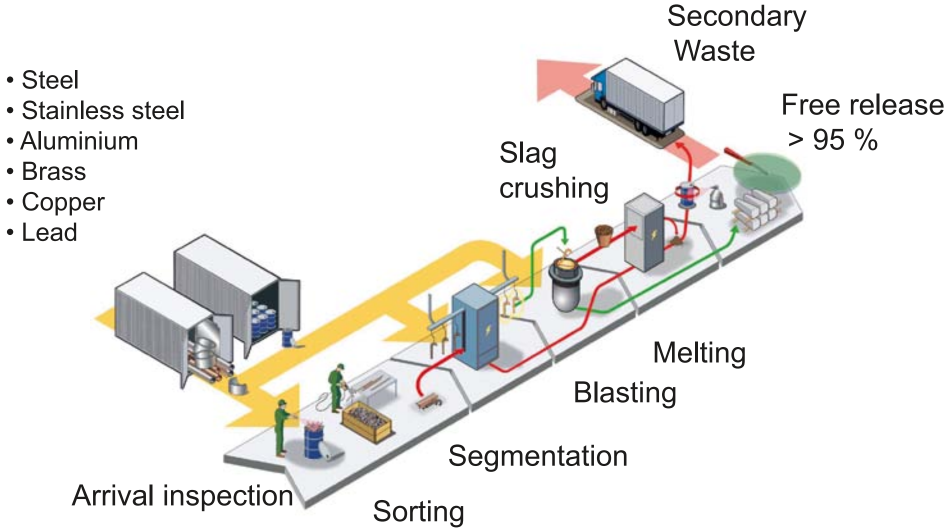

Figure 3-2. *Operations at the melting facility in Studsvik.*

Table 3-1. Other facilities for melting of radioactive material (IAEA 2006).

Country	Site	Type of metal	Radiological limits
France	CENTRACO	Mainly steel	β/γ 20,000 Bq/g, α 370 Bq/g
	INFANTE	Steel	250 Bq/g of ^{60}Co, other limits for other nuclides
Germany	CARLA	Steel, aluminium, copper, lead	β/γ 200 Bq/g, α 100 Bq/g
Russia	ECOMET-S	Steel	100 Bq/g

The German and Russian facilities are primarily, like the Studsvik facility, designed for melting low level scrap metal intended for free release or for manufacturing of casks or shielding blocks.

This is also the main task for the CENTRACO facility but it is also designed to treat material in the lower range of the ILW category and ingots with a dose rate up to approximately 5–6 mSv/h can be produced.

As is evident when comparing data from Table 3-1 and Table 4-1 none of the facilities are designed or equipped for the treatment of the components covered in this report.

4 Waste stream analysis

The waste types covered in this report are both waste that are not suitable for disposal in SFR due to a high inventory of long-lived isotopes and/or high dose rates (e.g. core grid and moderator tank) and waste planned for disposal in SFR (e.g. moisture separators).

From a treatment perspective the long-lived isotopes are of little concern. Instead the dose rate, mainly from gamma radiating nuclides such as ^{60}Co, will be a limiting factor.

The waste types included in this study are very heterogeneous from a radiological inventory point of view. The specific activity varies over several orders of magnitude, mainly depending on the distance to the core.

For the largest components within this study, the RPVs, the upper and bottom sections can most likely be subject to free release after treatment while the central part will require significant shielding during the entire management process and also after treatment.

4.1 Waste amounts and activities

The waste considered in this assessment comprises the core components and reactor internals from both BWR and PWR reactors. For PWR reactors, the RPV is also taken into consideration as the walls of the central part of the vessel have induced activity and therefore are not suitable for disposal in SFR.

The amounts of material from one reference reactor of each type, together with an average specific activity are given in Table 4-1. The data are based on the calculated nuclide inventory[1] of core components and reactor internals for two Swedish reactors, one BWR and one PWR. The activity values are calculated for 5.6 and 1 year of decay after shutdown, respectively.

Table 4-1. Mass and the specific activity for core components and reactor internals for the reference reactors. Note that BWR control rods and core instrumentation are not included.

Component	Mass (ton)	Specific activity (Bq/kg)
BWR		
Core grid	5.0	1.3E+12
Moderator tank	10.8	2.9E+11
Core spray	4.0	1.0E+10
Moderator tank cover	34.0	2.1E+09
Control rod guidance tubes	12.1	1.2E+09
Steam separator	18.5	2.9E+08
Moisture separator	22.0	3.6E+07
Total	**106.4**	
PWR		
Core baffle	14.0	1.5E+13
Lower grid plate	25.0	4.1E+12
Upper internals assembly	20.0	3.1E+12
Core barrel incl. thermal panels	35.0	2.2E+12
Reactor pressure vessel	245	1.1E+10
Total	**339.0**	

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[1] The data are based on calculation data by an external restricted source and are not referenced here.

It should be noted that the level of radioactivity in the RPV varies considerably between different parts. The central part is significantly more activated than the peripheral parts, e.g. the RPV head. However, data is given for one homogeneous component and the activity level is consequently overestimated for a large part of the RPV. It is hard to state quantitatively how large this part is due to lack of data, but an estimate is that 85% of the approximately 50 ton RPV head can be subject for free release. The fraction is likely to decrease steeply as the distance to the central part decreases. However, the results indicate that a significant portion of the material may be subject for free release after decontamination and melting. The overestimate should be kept in mind when viewing the data below.

The distribution of specific activity for the two reactor types are shown in Figure 4-1.

Based on the data in Table 4-1 the total material inventory including core components and reactor internals from the 9 BWR and 3 PWR reactors in Sweden is estimated to approximately 2,000 tons. This figure does not take into account the difference in design between reactors or the difference in decay time and should therefore be used only as an approximation. The distribution over specific activity of the total inventory is given in Figure 4-2.

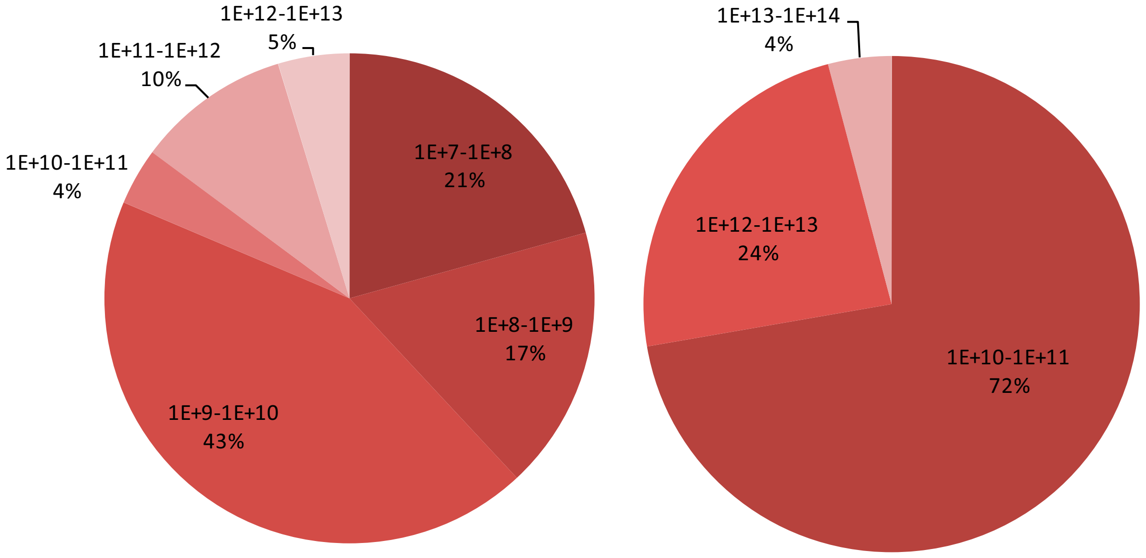

Figure 4-1. *The distribution of specific activity in the core components and reactor internals from a BWR (left) and a PWR (right) (Bq/kg).*

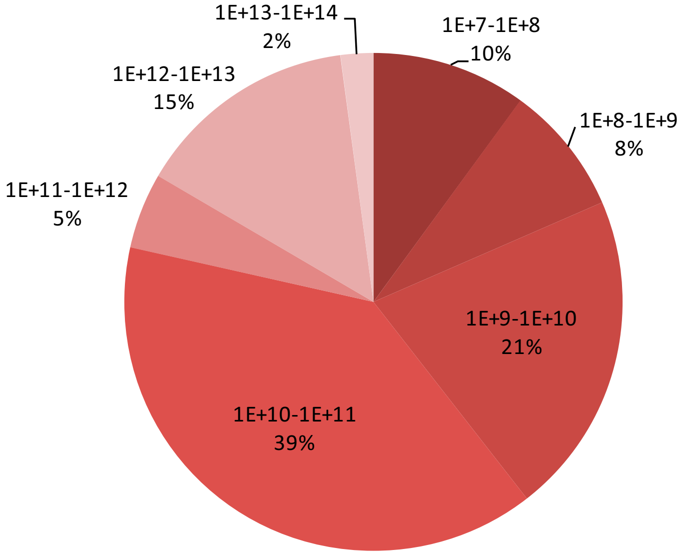

Figure 4-2. *The distribution of specific activity in the core components and reactor internals from the Swedish NPPs, both BWR and PWR (Bq/kg).*

4.1.1 Physical dimensions

The waste types covered in this study can, based on their physical dimensions, be divided into two main categories:

- Core components and reactor internals loaded in cassettes in steel tanks. These are transported in a suitable transport container.
- Large components, i.e. the PWR RPVs, transported in one piece with required shielding.

The external dimensions of the steel tanks are:

- Length 3.3 m.
- Width 1.3 m.
- Height 2.3 m.

The wall thickness of the steel tank can be 50, 100, 150 or 200 mm depending of the radiation level of the waste. The size of the cassette varies in order to fit the internal dimensions of the steel tank. Therefore the segmented waste also varies in size. The maximum weight of the cassette with waste is limited to 12 tons.

The external dimensions of the PWR RPVs are approximately:

- Height 13.5 m.
- Diameter 4 m.

4.2 Assessment of ingot dose rates from melting of core components and reactor internals

An assessment of the potential meltable fraction of core components and reactor internals from BWR and PWR units has been made by calculating the dose rates of the resulting ingots.

4.2.1 Method

For each type of waste component, the specific ^{60}Co activity at end of operation has been used to calculate the surface dose rate of a melted ingot with a weight of 630 kg. All activity has been assumed to remain in the metal, hence giving the ingot the same specific activity as that of the melted component. This is a slightly conservative estimate, especially for components in which the majority of the radionuclides are in the form of surface contamination. However, experience show that even in this case a large portion of the nuclides will remain in the ingots if no decontamination is performed prior to melting.

In order to reduce the dose rate of the ingots, the ILW in the melt can be mixed with LLW. The amount of LLW required to reduce the dose rate to 10 mSv/h and 100 mSv/h respectively, the so-called *dilution factor* has been calculated. This has been done using activity values for both immediate dismantling as well as after 20 and 50 years of decay.

The 10 and 100 mSv/h dose rates have been selected based on the following reasoning:
The current melting facility can handle ingots with a maximum dose rate of approximately 1 mSv/h. As a basis for the design and cost of the facility, certain limitations, such as waste acceptance criteria for treatment, have to be set. In this work, an increase in the dose rate criteria up to 10 and 100 mSv/h has been allowed.

Using the dilution factors, the total mass multiplication factor for each component can been calculated. For example, if a component has a dose rate of 1,000 mSv/h, a dilution factor of 10 is required to reduce the dose rate to 100 mSv/h. The mass multiplication factor is thus 10, since the total amount of material for disposal will be 10 times the weight of the component.

Using this data, the percentage of material possible for melting without the need for dilution has been calculated.

Dose rates have been calculated using the Microshield software package (Grove Software 2012), based on a modelled iron ingot of 100 cm height and 16 cm radius. The ^{60}Co activity has been assumed to be homogeneously distributed in the ingot. Build-up is taken into consideration.

It should be noted that the term dilutant only refers to the use of other meltable radioactive waste, preferentially LLW metallic waste. A mixing of the various component types discussed in this report could also achieve some dilution that would not lead to an increase in disposed material. This has, however, not been quantified in this report.

4.2.2 Results

The results are presented in Tables 4-2 and 4-3.

Table 4-2. Calculated ingot dose rates for the various core components and reactor internals.

Component	Dose rate ingot, no dilution (mSv/h) Direct melting	 20 years decay	 50 years decay
BWR			
Core grid	1.3E+05	9.0E+03	1.74E+02
Moderator tank	3.2E+04	2.3E+03	4.39E+01
Core spray	9.5E+02	6.9E+01	1.33E+00
Moderator tank cover	2.0E+02	1.5E+01	2.85E-01
Control rod guidance tubes	1.7E+02	1.2E+01	2.32E-01
Steam separator	1.3E+02	9.4E+00	1.83E-01
Moisture separator	1.6E+01	1.2E+00	2.24E-02
PWR			
Core baffle	1.7E+06	1.3E+05	2.42E+03
Lower grid plate	5.8E+05	4.2E+04	8.14E+02
Upper internals assembly	4.5E+05	3.3E+04	6.29E+02
Core barrel incl. thermal panels	2.4E+05	1.7E+04	3.28E+02
Reactor pressure vessel	3.9E+02	2.8E+01	5.51E-01

Table 4-3. Mass multiplication factors for the various core components and reactor internals.

Component	Mass (tons)	Mass multiplication factor, material diluted to 10 mSv/h ingot surface dose rate			Mass multiplication factor, material diluted to 100 mSv/h ingot surface dose rate		
		Direct melting	20 years decay	50 years decay	Direct melting	20 years decay	50 years decay
BWR							
Core grid	5.0	1.3E+04	9.0E+02	1.7E+01	1.3E+03	9.0E+01	1.74E+00
Moderator tank	10.8	3.2E+03	2.3E+02	4.4E+00	3.2E+02	2.3E+01	1.00E+00
Core spray	4.0	9.5E+01	6.9E+00	1.0E+00	9.5E+00	1.0E+00	1.00E+00
Moderator tank cover	34	2.0E+01	1.5E+00	1.0E+00	2.0E+00	1.0E+00	1.00E+00
Control rod guidance tubes	12.1	1.7E+01	1.2E+00	1.0E+00	1.7E+00	1.0E+00	1.00E+00
Steam separator	18.5	1.3E+01	1.0E+00	1.0E+00	1.3E+00	1.0E+00	1.00E+00
Moisture separator	22.0	1.6E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.00E+00
PWR							
Core baffle	14.0	1.7E+05	1.3E+04	2.4E+02	1.7E+04	1.3E+03	2.42E+01
Lower grid plate	25.0	5.8E+04	4.2E+03	8.1E+01	5.8E+03	4.2E+02	8.14E+00
Upper internals assembly	20.0	4.5E+04	3.3E+03	6.3E+01	4.5E+03	3.3E+02	6.29E+00
Core barrel incl. thermal panels	35.0	2.4E+04	1.7E+03	3.3E+01	2.4E+03	1.7E+02	3.28E+00
Reactor pressure vessel	245.0	3.9E+01	2.8E+00	1.0E+00	3.9E+00	1.0E+00	1.00E+00

The total amount of meltable material without dilution in the various scenarios is presented in Figures 4-3 and 4-4.

Note that the method of plotting only the meltable fraction without dilution means that all material above the dilution limit is excluded regardless of how much it exceeds the limit. This is evident in the PWR case where several of the plots are identical even though there is a large difference in the dilution factors.

4.2.3 Assessment

It should be noted that the current assessment is based only on the resulting dose rate of the ingots, and does not take other factors into consideration. Practical matters and risks are discussed later in this report.

For some waste types the data presented above misrepresents the meltable fraction. This is especially the case for the PWR RPV. For RPV's there is a significant gradient in the activation between the central parts close to the core and the peripheral parts, such as the RPV head. Since the RPV accounts for a large fraction of the total PWR material in this study a significant fraction of the PWR waste is expected to be treatable. To some extent such treatment is already performed at the Studsvik melting facility.

It is also important to note that the calculations presented above are entirely based on mass, and therefore does not take volume reduction into account. This method is motivated by the difficulty to estimate the relationships between initial volume, reduction in volume due to segmentation, packaging efficiency, radiological parameters such as the required thickness of shielding in packaging, etc. This means that dilution with other LILW may be an option depending on the relation to volume reduction.

For both reactor types it is apparent that the time for decay has a significant impact on the meltable fraction. However, due to the relatively high specific activities in the PWR internals this benefit is smaller for PWRs than for the BWRs for the times considered here.

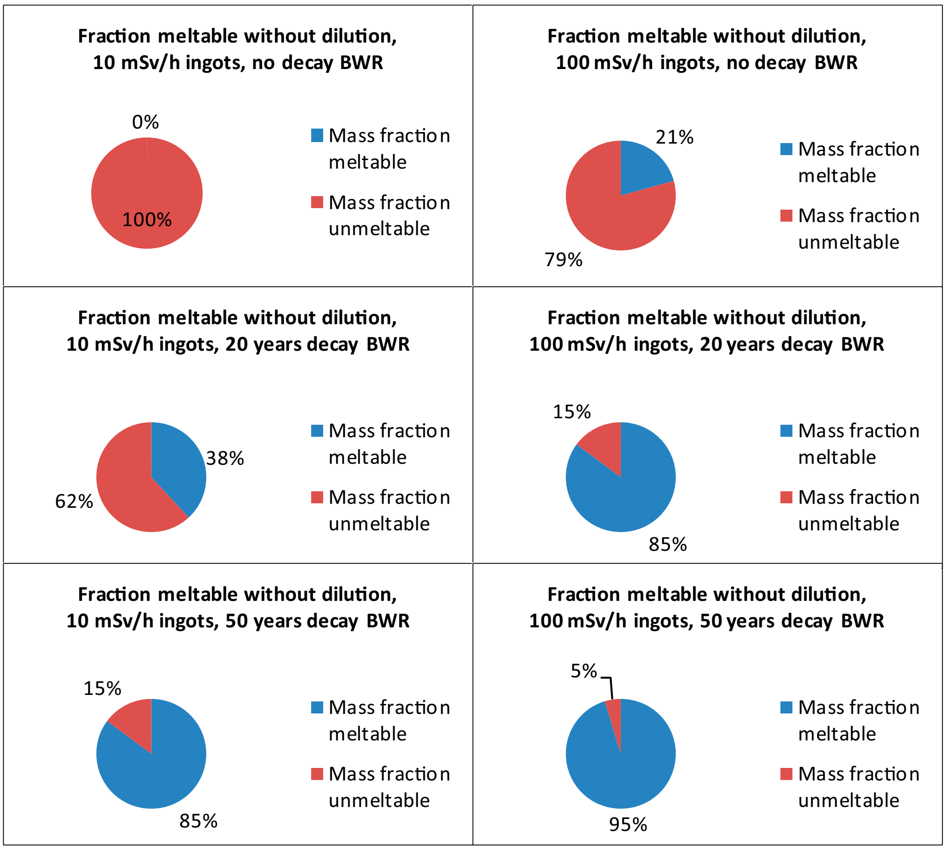

***Figure 4-3.** Percentage meltable material from BWR, various scenarios.*

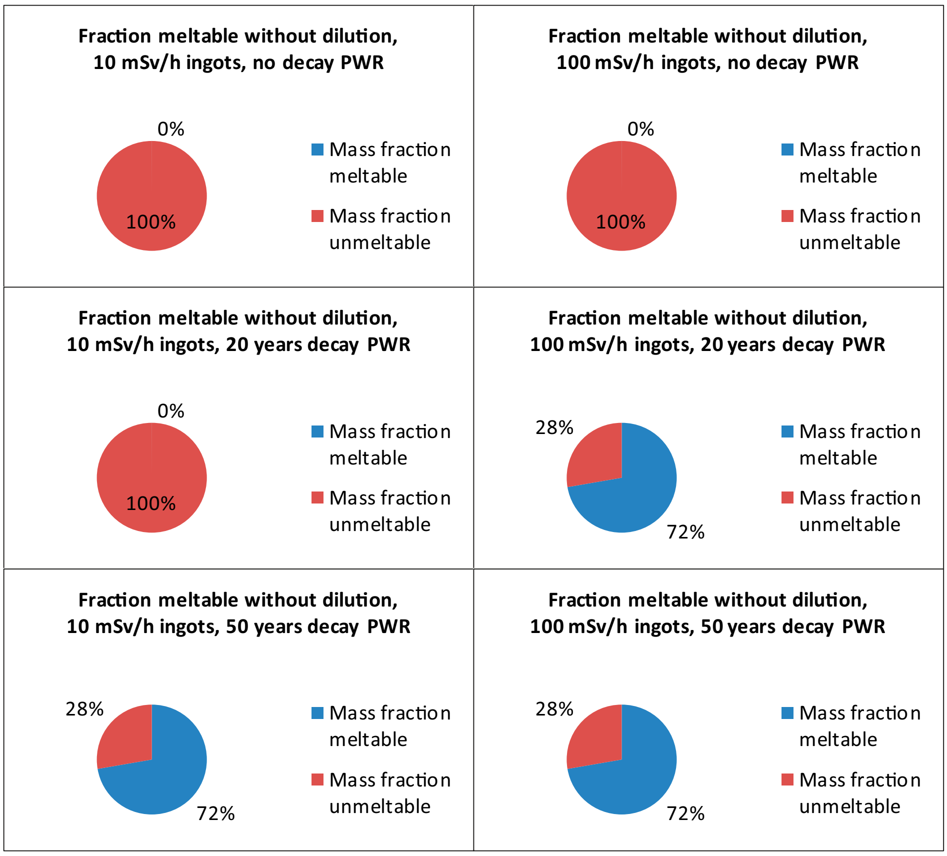

Figure 4-4. *Percentage meltable material from PWR, various scenarios.*

5 Requirements for the facility

The requirements on the facility for melting of ILW are presented below.

5.1 Requirements regarding waste acceptance

Functional requirements

1. Shall be able to safely transport, unload and handle steel tanks with
   a. Waste containing up to 5E+16 Bq.
   b. Gross weight up to 55 metric tons.
2. Shall be able to safely transport, unload and handle steel tanks with surface dose rates up to 200 mSv/h, and a hot-spot surface dose rate up to 300 mSv/h.
3. Shall be able to transport and unload waste packages from all existing ATBs.
4. Shall be able to transport, unload and handle all planned ATBs for SFL.
5. Shall be able to receive other types of ILW for treatment and packaging.
6. It must be possible to construct and operate the conditioning facility without unacceptable releases of radioactivity and without the risk of exposing the personnel to anything but a very low radioactive dose or other harmful substances.
7. Shall be able to transport, unload and handle the treatment of whole PWR RPVs.

5.2 Requirements for handling and treatment

Safety requirements

The metal charged to the melting furnace must not under any circumstances contain liquids, moisture or enclosed volumes. The presence of liquids and moisture in scrap metal can cause severe accidents when the material is melted. For this reason, under-water cutting of the components should be minimized or preferably avoided prior to melting.

Functional requirements

To provide for safe treatment and handling the following functional requirements must be fulfilled:

1. Safe handling and treatment of incoming waste with an operating situation focused on ALARA, BAT and low doses to staff and the surrounding environment require
   a. Dry unloading of the cassette with ILW from the steel tank.
   b. Standard active two stage ventilation.
   c. Vacuum drying of all types of waste packages in order to remove all traces of moisture.
   d. Remote handling of equipment for segmentation, loosing and tightening of bolts etc.
   e. Remote handling of equipment for waste conditioning and re-packing.
   f. Remote handling of waste transportation e.g. overhead crane in the facility.
2. An overhead crane with a capacity of 60 tons and other types of equipment for handling of the steel tanks and waste cassettes must be available.
3. Shall be able to handle segmentation and treatment of whole PWR RPVs, with conditioning and re-packing into suitable waste packages.
4. Equipment and methods for measuring of activity and dose rates on conditioned and re-packed waste packages are needed. Needed space for this must be provided.
5. Equipment for checking that conditioned and re-packed waste fulfils the specified requirements shall be available. Needed space for this must be provided.

5.3 Requirements regarding outgoing waste

Functional requirements

1 The waste shall be conditioned in accordance with the set waste acceptance criteria (WAC) for the repository. In case the WAC has not yet been specified, all waste should be retrievable and the packages possible to condition to the final conditions without any further management of the waste in the package.

2 Waste packages shall be placed in SKB's ATBs.

3 The surface dose rates on waste packages ready for disposal shall be less than 200 mSv/h.

6 Treatment concept and process flow

In this chapter a brief overview of the envisaged treatment concept is presented. A graphical representation is shown in Appendix A.

6.1 Transportation and unloading

Due to the anticipated high dose rates of the waste considered in this report, remote handling is necessary. A purpose built unloading area where transport containers can be opened and waste packages unloaded using only remote equipment is required.

The transport container lid is opened, exposing the steel tank. A strong-back is placed on the steel tank which enables an overhead crane to lift out the steel tank. Due to the steel tank dimensions this requires additional height of 2.3 m plus that of the lifting equipment itself.

At arrival, the lid of the steel tank is bolted. A mechanism for unbolting or cutting the bolts will be needed in order to remove the lid and expose the cassette with ILW inside the tank.

The cassette is lifted out using the lifting mechanism and the lid of the cassette is removed, exposing the waste for further treatment. This step might alternatively be made in the pre-treatment hot-cell if deemed more appropriate from a safety point of view, see below.

For PWR RPVs a separate area in the facility will be used for segmentation.

6.2 Temporary storage

A buffer storage area for incoming steel tanks will be needed. This area should preferably be connected to the unloading area and accessible by the lifting equipment described above. Alternatively, the use of existing buffer storage areas on the site is also possible provided that the transportation can be performed safely.

6.3 Pre-treatment

6.3.1 Core components and reactor internals

In order to be able to place the ILW in the cassette, large waste components have been segmented at the waste producers' sites. However, additional segmentation might be needed prior to melting in order to place the ILW in the loading basket for the furnace. For segmentation, remotely operated saws, cutting equipment etc can be used.

There is also a need to inspect and, if needed, physically manipulate the material in order to make it more suitable for melting. Two examples of this are the need to open closed compartments and to compact pipe-shaped objects in order to reduce the risk of floatation during melting.

In order to realize the pre-treatment concept, a hot-cell will likely be required. The unloaded waste cassettes are placed on a conveyor and transported from the loading area into a docking station at the hot-cell. The cell is equipped with remote manipulators by which the operators can unload waste from the cassette onto the main work area of the hot-cell. By using manipulators the operator segments, compacts and otherwise pre-treats the waste into a form suitable for melting.

After pre-treatment, the waste is placed in a shielded charging basket purpose built for unloading waste into the furnace. This basket is transported to the furnace by a conveyor or by lifting.

6.3.2 Large components

Large components such as the PWR RPVs require a lot of space for the pre-treatment, which makes the shielding complicated. Compared to the core components and reactor internals, the RPVs contain material which probably can be treated for free release. To be able to meet the free release criteria the material must be decontaminated.

It is important to arrange proper shielding and to make arrangements to prevent airborne contamination.

It is most likely possible to transfer parts of the waste to other categories (LLW). This includes peripheral parts of the RPV which could be subject to free release. This would require decontamination of the material using sheering, blasting, etc. Such handling is likely to be performed in another area in order to avoid contamination of material potentially suitable for free release.

6.4 Melting

The waste is loaded into the furnace from the shielded charging basket.

During the melting process there is a need for agitation of the melt in order to ensure proper melting. Due to the high dose rate, this must be performed by a manipulator, either automated or manually remote controlled.

The generated slag is scooped up by the agitation mechanism and loaded into a container for cooling prior to further conditioning.

The molten metal is poured into one or several moulds. The ingot is fitted with a lifting hook before it solidifies.

RPV material that may be subject to free release after melting should be transferred to a LLW melting facility in order to reduce the risk of cross contamination.

6.5 Conditioning of processed metal and generated secondary waste

The ingots are, as mentioned above, fitted with lifting hooks during cooling. This enables remote lifting of the ingots for transport to a packaging area where the ingots are placed in their intended disposal containers. Samples from the melt are taken during processing for determination of the activity content.

Secondary waste is produced in several steps during the process.

Segmentation techniques such as sawing and cutting produces secondary waste in the form of metallic splinters, dust etc. This waste is collected in the hot-cell and packaged for disposal.

Melting produces a slag residue containing oxides, impurities etc from the metal. The slag normally also contains the alpha emitting radionuclides present in the original material. Since the slag forms a cap above the melt, some of the volatile nuclides are trapped in the slag, but most end up in the bag house filters in the off-gas system.

The slag is scooped up into a container near the furnace. This container is transported to the packaging area by lifting or conveyor and packaged in disposal containers.

Secondary waste is characterized with regards to the activity content.

6.6 Storage

An indoor area for storage of outgoing material is needed. In this area the conditioned waste is stored until it is transported to the disposal site or returned to the customer. The requirement for this area is mainly to ensure adequate radiation protection and to prevent accelerated degradation of the waste packages.

7 Technical aspects and requirements

In this chapter some specific technical issues regarding the operation of a facility for melting of ILW are discussed. The discussion is based on experiences from existing melting facilities and on the know-how in the Studsvik organization regarding management of ILW. The aim is to highlight both the possibilities and the challenges.

7.1 General aspects on the facility

7.1.1 Location

The transport system for radioactive waste in Sweden is mainly sea-based. For this reason it is advantageous if the facility is located along the coastline with access to a harbour.

From an infrastructure and licensing point of view, such a facility is preferably located at one of the existing nuclear sites in the country, either at an NPP site, at the Studsvik site, or at/near the location of the final repository.

Due to the potential intermittent periods with few on-going decommissioning projects, staffing and keeping of know-how are potential risk factors. The Studsvik site and the final repository site are likely to offer advantages in this regard over the NPP sites which will be decommissioned and dismantled while the melting facility is in operation.

Furthermore, the existing infrastructure including the LLW melting facility and know-how is in favour of Studsvik. On the other hand, the repository site offers the advantage of less transportation.

7.1.2 Capacity

The capacity of a facility for melting of core components and reactor internals will by necessity be tied to the planned decommissioning program. The expected starting dates for the decommissioning for the Swedish commercial reactors are presented in Table 7-1.

From Table 7-1 it is evident that the Swedish decommissioning projects will generate metallic ILW in campaigns with intermittent periods of no generation.

If the discussed facility is used only for melting of LL-ILW, it is reasonable to assume that the waste generated by one reactor can be processed in less than one year. For this reason it is unlikely that limits in management capacity will impose any problem. Due to the relatively limited volume of waste, it is also expected that the buffer storage can be dimensioned for storage of waste from more than one reactor.

Table 7-1. Expected start of decommissioning of the Swedish NPPs.

Year	Reactor
2020	Barsebäck 1
2020	Barsebäck 2
2029	Ringhals 1
2030	Ringhals 2
2035	Forsmark 1
2036	Forsmark 2
2037	Ringhals 3
2038	Ringhals 4
2038	Oskarshamn 1
2039	Forsmark 3
2039	Oskarshamn 2
2048	Oskarshamn 3

For reasons related to economy, facility maintenance, staff issues, know-how etc, the above decommissioning schedule will likely be problematic. This is especially in the case of the intermittent periods when no decommissioning activities are performed.

For this reason it might be expected that such a facility would be dimensioned also for waste from other operations generating ILW and from decommissioning projects outside of the nation. It is also likely that the facility would be used for SL-ILW not suitable for treatment in other facilities due to activity restrictions.

In doing so, the capacity of the facility would be better utilized, but a more flexible facility and most likely more space in the form of buffer storages etc would be required.

The capacity requirements are not further specified.

7.1.3 Dimensions

The physical dimensions of the facility need to be based on a detailed study of the layout when the waste acceptance criteria for treatment are set and the production capacity decided. At this stage only some general remarks can be given.

The facility can be divided into five major parts:

- Arrival and unloading areas.
- Pre-treatment hall including segmentation cell.
- Melting hall.
- Secondary waste conditioning area.
- Storage area.

In addition to auxiliary areas for service systems, there will be a need for changing rooms for the staff, radiation protection and management offices etc.

The height of the building will be determined by the maximum expected lifting height plus that which is needed by the lifting equipment itself. The dimensioning of the facility will probably be based on requirements set by the lifting of the steel tanks from the ATB. A building height of minimum 12 m is expected.

The land area required for a facility is expected to be in the range of 2,000 to 3,000 m^2 excluding buffer storage areas, but can be significantly less if the facility is built as an extension to an existing nuclear facility.

7.1.4 Construction

Construction of the facility itself does not, except for the barrier and shielding arrangements, differ from other comparable industrial facilities from a technical point of view. Locating the facility at an existing nuclear site may offer some additional challenges due to increased security during the construction period, but will on the other hand reduce the investments in physical protection arrangements such as fences etc.

7.1.5 Safety systems

Construction

Due to the combination of molten metal and the high radioactivity inventory, it is important that the construction is made to withstand both internal and external events which could have an effect on the facility.

Ventilation

The high activity in combination with treatment such as segmentation and melting will require the use of ventilation and filtration systems with a high cleaning efficiency. This will likely consist of advanced filter trains in parallel.

Radiation protection

Adequate radiation shielding and cells to prevent airborne contamination is necessary to ensure the working conditions in the facility.

Physical security

Due to the sensitivity of the facility, the need for physical security will be similar to that of other nuclear waste treatment facilities. The physical security would need to be in accordance with that regulated for category 3 facilities in SSMFS 2008:12 (SSM 2008a).

7.2 Waste acceptance and unloading

7.2.1 Acceptance criteria

The facility must be designed to handle waste with very different levels of activity in order to process the material listed in Table 4-1. Whether this is reasonable or not is discussed in Chapter 12.

It is expected that all material to be processed, except large components, will arrive in similar types of waste packages and transport containers enabling a uniform approach to handling of incoming waste.

Due to the relatively narrow range of waste forms discussed in this report, the variations in the incoming waste are likely to be well known. This will allow for a streamlining of the handling since the likelihood of unexpected situations are low.

This also allows for the facility construction requirements to be well known from the onset.

The acceptance criteria for large components are most likely, due to size, those which have the largest impact on the facility.

7.2.2 Lifting and unloading

As mentioned above, most incoming waste is expected to follow the same packaging concept, i.e. with few types of waste packages and transport containers.

The unloading and lifting equipment will therefore be suited especially for these types of waste packages and containers. At the time of this report, waste is already stored in steel tanks in interim storages in Sweden. Whether such steel tanks will be used at the time of decommissioning is not known.

Due to the high dose rates, all lifting and unloading will be performed remotely. The incoming waste packages will be required to provide the means for such handling, such as containing features where lifting equipment can get hold, etc. The expected weight of the packages is up to 60 tons.

An area of concern is the waste packages that have already been stored for a long time. The physical condition of these may require additional handling, for example in the case of corrosion on features necessary for the handling of the package.

In any case, the need for a uniform transport concept will require that design parameters of the equipment for incoming waste are well known and standardized.

For the lifting and unloading of RPVs, the same lifting and loading operations that are planned to be performed at the NPP can be used in reverse.

7.2.3 Internal transport

The transport of waste within the facility is likely performed either by lifting or by some form of conveyor (for example on rail). Lifting offers more degrees of freedom, but also offers more challenges in equipment requirements, loading/unloading etc. Lifting also has potentially larger consequences in case of a failure.

Three major internal transport routes have been identified:

- Transport between the unloading position and segmentation hot-cell.
- Hot-cell to furnace.
- Ingots from the pouring position to the disposal container position.

In addition, there are certain smaller transport streams for secondary waste and material that shall be transferred to a LLW melting facility.

A conveyor is likely a suitable option for the transport from the unloading area to the pre-treatment hot-cell. The conveyor will transport the waste package to a docking station at the hot-cell, where manipulators lift the waste out of the package and into the work areas of the hot-cell.

The transport route would be supplied with adequate radiation shielding.

7.2.4 Operational safety

The steps as outlined above are performed remotely with no need for staff being in the vicinity.

The main cause of concern, in addition to the conventional risks with melting of metals, are the high dose rates.

Recovery of a frozen melt in the furnace, bridging in the furnace, fire, dropped packages or packages not possible to disconnect from the lifting device are occurrences which are likely to be problematic to manage due to the high dose rates.

Of highest concern are scenarios which have to be managed immediately such as fires and bridging in the furnace.

Factors such as those listed above will have a large impact on the overall feasibility of the facility.

7.3 Pre-treatment

7.3.1 Extent of pre-treatment

The extent to which waste will require pre-treatment will depend on the specific waste type as well as the extent to which such treatment has been performed at the waste producer's site.

The main form of pre-treatment will be segmentation, compaction, or other methods of physical preparation of the waste to suit the requirements of the furnace.

Segmentation is likely to be performed using mechanical equipment such as saws. Thermal cutting may be needed for certain waste forms.

Compaction is likely needed for some waste forms, such as the steam separator tubes. Compaction will reduce the risk of floatation during melting.

Treatment in order to remove contamination is not expected to be performed. For the core components the majority of the activity is in the form of activation with little possibility for reduction through pre-treatment. For the reactor internals there may be a possibility to reduce the contamination levels through decontamination, but this would not lead to significant advantages since the contamination would instead be transferred to a secondary waste stream without the possibility for free release of the primary waste.

The exception to this is parts of the RPV which are expected to be less contaminated. As mentioned previously it is expected that such treatment is performed in other areas or in another facility in order to reduce the risk of contaminating material potentially classifiable for free release.

7.3.2 Hot-cell

In the pre-treatment hot-cell, remotely controlled manipulators will be used to lift the waste from the cassettes as well as to handle and manipulate the waste. The control station may be located adjacent to the hot-cell or further away if monitors are used.

The former option has the benefit of giving the operator a better overview of the operations performed. However, this requires that appropriate radiation shielding such as lead glass windows is used in order to keep the average dose rate at the operator control stations below 5 µSv/h.

If a remote control station is used the requirements on the radiation shielding are reduced, but instead operating is likely to be less efficient due to the reduced overview when not having direct access to the hot-cell.

The hot-cell will be the area with the highest risk for spreading of contamination. This will require the use of equipment to collect secondary waste created during the processing of the waste as well as having a high-efficiency filtered ventilation system.

After pre-treatment, the waste ready for melting is placed in a shielded charging basket purpose built for the furnace operation.

7.3.3 Docking

The hot-cell will require a docking station for incoming and outgoing waste.

The incoming waste docking station will be connected to the transport system of the facility so that the waste cassettes can be transported remotely from the unloading area to the hot-cell. This docking station is ideally constructed in a way that minimizes the risk of contamination of the packaging. From the docked position manipulators will be used to lift waste from the package and onto the work area.

If unloading of the cassette from the steel tank must be performed in the hot-cell, additional lifting equipment may be necessary.

A docking station for outgoing waste will be needed in order to transport the waste from the hot-cell to the furnace, as well as secondary waste and otherwise not treatable waste from the hot-cell. This is expected to be performed by docking the waste basket to the hot-cell and lifting it using an overhead crane.

7.4 Melting

7.4.1 Normal operation

During normal operation the furnace will be fed using a purpose-built shielded charging basket.

Agitation of the melt will be required to ensure that melted material does not get stuck. This will be performed using a remote controlled mechanism which may be operated either automatically or manually.

7.4.2 Disruptions to normal operation

Disruptions to normal operation of the furnace may be caused by different initiating events.

Loss of power may be caused by disruptions in the grid electric supply, or by electrical failure in the equipment itself. When a disruption occurs, the melt may cool and lodge itself in the furnace. If this happens, with the conventional induction furnace design it is likely that the solid block will have to be cut and the refractory removed to allow for removal of the solidified melt. Due to the radiological characteristics of an ILW melt, such work will be complicated.

There is a risk for explosions in or near the furnace due to vapour expansion. This could be caused e.g. by contact between the melt and liquids in the waste or from the cooling system in case of breakthrough.

The consequences of a vapour explosion can partly be mitigated by designing the furnace foundation in such a way that the forces created by the accident are distributed in a controlled manner. Still this is a very dangerous situation.

From experience it is known that loss of power occurs relatively frequently, on the order of a few times per year and that explosive incidents also occur, albeit much less frequently.

There are also other potential accidents that could occur, such as a release of the melt after a breakthrough in the furnace. This is, however, less likely than the above.

The ability to contain these situations is likely one of the main limiting factors in the operation of a facility for melting of ILW.

8 Working environment

The requirement regarding working in a radiological environment is governed by labour laws as well as regulations specified by the Swedish Radiation Safety Authority (SSM). Such regulations can mainly be found in SSMFS 2008:51 (SSM 2008b).

In addition to the radiological and nuclear regulations, also the conventional regulations apply.

8.1 Worker protection

8.1.1 Worker protection during construction

During construction of the facility, the working conditions do not in principle differ from construction of a comparable non-nuclear facility.

8.1.2 Worker protection during operation

While the melting facility in itself is a complex industrial facility with several risks involved, the risk to personnel from industrial accidents are less likely due to the remote operation of the industrial processes.

8.2 Radiological environment

During operation, it is the operators' responsibility to ensure that the dose burden to the staff is kept as low as reasonably achievable. The maximum allowable equivalent dose to a worker specified in SSM (2008b) is 50 mSv/year or a total of 100 mSv during five consecutive years.

For the operator stations the average dose rate should be below 5 μSv/h.

As outlined in the treatment concept the whole normal operation of the facility is expected to be performed by remotely controlled equipment or by the use of manipulators. For this reason the dose burden during normal operation is expected to be low. Radiological shielding will be used in order to comply with set dose rate limits in areas frequented by people and staff will be required to wear dosimeters.

The main challenge is in non-normal operation. Due to the potential consequences of an accident it is of importance to be able to show that probabilities are low and/or that restoration can be performed with acceptable radiological impact.

As has been outlined in Chapter 7, based on experience from facilities for melting of LLW, the probability of non-normal occurrences are relatively high. In a melting facility for ILW certain situations must be able to be handled remotely.

8.3 Humans – Technologies – Organization

In any nuclear facility, it is of utmost importance that safety is of highest priority, and that the conditions for allowing safe practices are provided.

In a remote controlled facility the human-machine interface will be important. The equipment used should function as planned as far as possible even in the case of operator error and during abnormal situations. This may include incidents such as lifting devices not being able to release a heavy load during lifting, etc. However, the risk of occurrences not possible to foresee can never be fully eliminated.

For this reason, in conjunction with the specific waste discussed in this report, the organizational focus on safety must be highly prioritized. This includes actively encouraging safety evaluations and improvement in any and all risk moments.

9 Discharges and environmental effects

9.1 Discharges of radioactivity and hazardous elements

The amount of discharged radioactivity to the environment is not quantifiable at this stage, since the operational parameters are not known. However, a comparison can be done with the existing melting facility at Studsvik.

Release to air

Based on data from the safety assessment report of the current melting facility, the average dose burden to a member of the critical group from release to air has been in the order of 1E-07 mSv/year during 2000–2005. This is several orders of magnitude below the limit of 0.1 mSv/year.

In the current melting facility waste with surface dose rates up to 0.2 mSv/h is accepted, although higher dose rates can be allowed after consultation and approval. Reactor internals such as steam separators which are mainly surface contaminated and not activated have surface dose rates in the order of 100 mSv/h. A rough assumption is thus that the surface contamination may be in the order of 1,000 times higher for the components in the LL-LILW facility. Under the assumption that a similar fraction is released to air the dose burden to a member of the critical group would still only reach 1E-04 mSv/year.

This rough comparison does not take into account increased filtration efficiency which would likely be required for the LL-LILW facility.

It should be noted that the majority of the activity is in the form of activation products in the metal. Such activity is to a large degree expected to stay in the material during the treatment process. However, some nuclides, such as ^{3}H and ^{14}C, are expected to be released. These are not normally found in large quantities in surface contaminated metal, and were therefore not included in the safety assessment report for the current melting facility.

According to SKB (1999) the ^{3}H and ^{14}C content in core components and reactor internals are approximately 2.5E+15 Bq and 1.7E+14 Bq respectively. The corresponding dose burden to a member of the critical group near the Studsvik site from these two nuclides are 1.72E-17 mSv/Bq and 1.30E-15 mSv/Bq respectively. The corresonding dose burden from these two nuclides under the assumption of full release without filtration is 0.043 mSv and 0.221 mSv respectively. These should, however, be distributed over the entire operational time period of the facility.

Release to water

The release to water is not easy to compare since the safety assessment report for the current melting facility only reports dose burden from release to water for the entire Studsvik area combined. Water usage in the controlled areas of the treatment facility is also expected to be very limited due to the risks with water present in a foundry environment.

9.2 Environmental effects

Apart from the radiological effects described above, the facility is expected to have effects similar to those of comparable industrial facilities. Due to the low capacity of the facility, the total environmental impact will be very small.

The main effect is through energy usage. The current LLW melting facility has an energy consumption of approximately 1.5 MWh per ton of melted material. This number is the total energy consumption, including heating and electricity of auxiliary facilities such as offices etc. Similar usage may be expected for the ILW facility.

10 Cost estimation

A rough cost estimate has been made based on a comparison with the LLW melting facility in operation. Due to the conceptual level of the facility it is not possible to give a precise estimate. It should be noted that this cost estimate is based on the assumption that the melt has a relatively low dose rate, in the order of 10 mSv/h. If this is increased further it is likely that new technology will need to be employed in order to further reduce risks, see Chapter 11. This, consequently, increases the cost by an unknown amount.

10.1 Design and licensing of facility

The cost of design and licensing of a LLW melting facility is in the range of MSEK 5–10. An ILW melting facility is more complex to design. Also licensing is expected to be more costly and time consuming as it is the first of its kind. Based on this, the cost for design and licensing is expected to be at least a factor 3 higher than for a LLW melting facility.

10.2 Construction and commissioning

The construction and commissioning costs depend on the design and the level of automation. A fairly rough cost estimation is in the range of MSEK 200–300. The corresponding cost for a small scale LLW melting facility is in the range of MSEK 50–100.

10.3 Operation

The cost of operation of a facility depends largely on the design of the facility and whether the facility will have to carry the full cost for all competences and training required or if the cost can be shared with other facilities on the actual site. Also the level of automation as well as if the operations will be one or more shifts per day affects the operational cost.

An estimated annual operational cost for a small scale ILW melting facility operating with one shift per day is in the order of MSEK 10.

10.4 Decommissioning

The decommissioning cost is estimated to be in the range of MSEK 20–30 but could vary significantly with the size, design and the level of contamination.

11 Risk analysis melting ILW materials

In this chapter a preliminary risk analysis for processing of metallic core components and reactor internals is presented. This is mainly based on Studsvik's experience with operating a similar facility for LLW.

The existing LLW melting facility in Studsvik is in many aspects designed similar to a conventional foundry. However, the LLW melting facility is also provided with a decontamination step before melting. This is not planned for the ILW melting facility. Apart from this, the major difference between the ILW and LLW facilities is the shielding and the need for remote operation.

All types of operations with molten metal involve significant risks. Such risks are well described in the literature for both conventional and LLW melting facilities. This risk analysis therefore focuses more on the radiological risks from melting of ILW components.

Consideration is taken to effects on the facility, health and environment.

11.1 Definition of used terms

The following terms are used in the safety analysis.

Event sequence	Describes the events that follow one another or a combination of events independent of each other that leads to a described consequence.
Cause	The event that starts a passage of events.
Barrier	The physical barriers to stop radioactivity from entering personnel and environment.
Consequence	Unwanted effects of a mishap.
Preventative measures	Measures to avoid the passage of events to occur such as reducing the risk for the cause, strengthening of barriers, mitigation of consequences etc.

11.2 Method of risk analysis

At this stage, when the facility is only conceptually discussed, a preliminary risk analysis method based on Davidsson (2003) is employed. The starting point is to identify incidents or events, and the various developments that may result from these. Each passage of events is analyzed and classified according to a scale for the probability of the event to occur, see Table 11-1. Similarly, the consequences for the facility, health for workers and the public, as well as impact on the environment are analyzed and classified according to Tables 11-2, 11-3 and 11-4. Based on these, a risk value is calculated by multiplication of the individual factors.

Assessments were performed by senior experts with experience from the existing melting facility in Studsvik.

11.3 Classification of probabilities and consequences

Tables 11-1–11-4 below describe used classification for probability and consequences for facility and environment, as well as for health of workers and the public.

Table 11-1. Classification of probability for analyzed passages of events.

Class no	Description	Corresponding frequency
1	Very low probability	< 1/100 year
2	Small probability	1/10–1/100 year
3	Probable	1/1–1/10 year
4	High probability	Sometimes annually
5	Very high probability	Many times a year

Table 11-2. Classification of consequence for facility.

Class no	Consequence
1	None or little
2	Repair and/or replacement of components – maintained operation
3	Shorter operation shutdown (1–30 days) for maintenance
4	Longer operation shutdown (more than 30 days) for extensive measures
5	Resetting of facility is not possible

Table 11-3. Classification of consequence for health (workers and public).

Class no	Consequence
1	Individual dose < 1 mSv
2	1 mSv < Individual dose < 6 mSv
3	6 mSv < Individual dose < 50 mSv
4	50 mSv < Individual dose < 100 mSv
5	100 mSv < Individual dose

Table 11-4. Classification of consequence for environment.

Class no	Consequence
1	No cleanup efforts, small spread
2	Simple cleanup efforts, small spread
3	Simple cleanup efforts, wide spread
4	Difficult cleanup efforts, small spread
5	Difficult cleanup efforts, wide spread

11.4 Description of event sequences

The type of accidents associated with the operation of a melting facility for core components and reactor internals is assumed to only marginally differ from those associated with similar activities in the conventional metal casting industry or the current LLW melting facility. However, the radiological consequences from a mishap or a technical failure differ widely.

Three critical and at the same time possible accidents were identified:

- Activity release due to vapor explosion.
- Activity release due to ladle breakthrough.
- Consequences of failure in the hot-cell or furnace chamber not possible to remedy using remote equipment.

11.4.1 Vapor explosion

Cause

Material containing moisture and/or enclosed spaces may, due to rapid expansion of gases when heated, cause an explosion and/or violent boiling.

Event sequence

The rapid expansion of gases may lead to ejection of molten radioactive metal from the furnace into the furnace hall. If there is a large amount of liquid the explosion may damage or destroy technical barriers such as facility walls.

Probability

For the LLW melting facility the probability classification for this event has been judged as 3. While the ILW facility is intended for a more homogeneous waste form than that of the LLW facility, the same classification number is used for the ILW facility. The main motivation for this is the underwater storage and segmentation that is often employed for core components and reactor internals.

The probability is classified as class 3.

Consequences

Facility

The consequences for the facility ranges from relatively mild to very severe depending on the force of the explosion as well as the type of waste being melted.

Non-radiological consequences may be physical damage or destruction of equipment and facility barriers, such as walls.

Due to the radiological consequences (see below) a longer operational shutdown would likely be required. Cleanup efforts would include cutting of solidified metal in a problematic radiological environment requiring use of remote technology before damage and repair requirements can be assessed.

Therefore the facility consequence is classified as class 4.

Health

Even though there is a risk for direct physical harm to operators for example in the control room and hot-cell, this analysis focuses mainly on the radiological impact.

The extent to which remote equipment could be used in the decontamination effort will largely determine the health consequences to the workers. It is reasonable to assume that there will be a need for workers to participate manually in the effort. Due to the potentially large dose rates and the physical environment, it is possible that the maximum allowable dose burden to a worker will be reached.

Therefore, the health consequence is classified as class 3.

Environment

No major consequence for the environment is expected as most of the radioactivity is bound to the material. In a severe accident with damage of the technical barriers some activity may escape, requiring the need for a smaller cleanup. While the dose rates may be high, it is assumed that a small spread could be cleaned up relatively easy.

Therefore the environmental consequence is classified as class 2.

11.4.2 Activity release due to ladle breakthrough

Cause

A ladle breakthrough involves loss of containment of the melt due to damage of the ladle. This may be caused e.g. by increased wear due to overheating in the melt, or from physical factors such as mechanical stress and impact from the waste.

Event sequence

A ladle breakthrough may lead to spread of molten metal in the furnace hall.

Molten metal coming into contact with the surrounding cooling equipment may cause a steam explosion.

Probability

For the LLW melting facility the probability classification for this event has been judged as 3. The ILW facility is likely to have additional safety measures employed, such as continuous temperature measurement of the ladle.

The probability is therefore classified as class 2.

Consequences

The consequences of a ladle breakthrough will depend on the event sequence. The most severe is when the molten metal comes into contact with the cooling system causing a vapor explosion.

The basic consequences are assumed to be similar to those of the vapor explosion above. While the ejection of molten metal is likely more local in the ladle breakthrough scenario, the consequences are judged to be similar.

The consequences are therefore classified the same as those for vapor explosion:

- Facility: 4.
- Health: 3.
- Environment: 2.

11.4.3 Technical failure inside hot-cell or furnace chamber not possible to correct with remote tools

Cause

The loss of electric supply or technical failure in the furnace causes loss of power supply. If not remedied quickly this could lead to that the melt solidifies.

Event sequence

A melt that is solidified due to cooling after loss of power cannot be removed nor re-melted. This may occur especially fast if there is unmelted material in the furnace.

For a cylindrical furnace similar to that of the current LLW facility, the solidified melt has to be cut out and the refractory material replaced.

Probability

For the current LLW facility, this type of event happens relatively often, in the order of a few times per year.

It may be possible to reduce the risk by adding a backup power supply and designing a furnace able to re-melt the solidified melt. It is, however, not known how well such measures can be employed.

The probability is therefore classified as 3.

Consequences

Facility

An unscheduled replacement of the refractory (relining) in the furnace would be required. Relining is normally done a number of times per year.

In a severe case, the whole furnace may need to be removed for separation of the solidified melt, e.g. inside the hot-cell. In a worst case scenario, this may even lead to a need to cut the furnace itself in pieces.

The former is more likely, and therefore the facility consequence is classified as 3.

Health

It is unknown to what degree remote equipment can be used to cut a solidified melt. It is therefore assumed that personnel may need to be employed.

Depending on the activity content in the melt, the radiological impact may be severe. For this reason it is assumed that workers may reach the maximum allowable dose of 50 mSv.

Therefore, the health consequence is classified as 3.

Environment

This event does not have any environmental impact.

Therefore, the environmental consequence is classified as 1.

11.5 Results from risk analysis

Results from the risk analysis are summarized in Table 11-5. Events with risk numbers above 5 are assumed to indicate considerable risk, meaning that preventative actions are motivated.

Table 11-5. Results from risk analysis.

Event sequence	Probability	Consequence			Risk		
		Facility	Health	Environment	Facility	Health	Environment
Activity release due to vapor explosion	3	4	3	2	12	9	6
Activity release due to ladle breakthrough	2	4	3	2	8	6	4
Technical failure inside hot-cell or furnace chamber not possible to correct with remote tools	3	3	3	1	9	9	3

11.6 Preventative actions

In order to reduce the risks above, some preventative actions have been identified.

In order to reduce the risk for over-boiling, the following preventive actions can be made:

- Detailed construction drawings of all core components and reactor internals should be used to plan an optimum segmentation before melting. The waste producer should provide information on the pre-segmentation that has been performed.
- Segmentation of components in a way to ensure that cavities are not present.
- Preheating of waste. The heat from the furnace can be used in a separate preheating system similar to conventional preheating system used in scrap metal based steelmaking.
- Preheating of slag additives.
- Enhanced protection barrier around the furnace to withstand a possible explosion.
- Careful embedding of equipment with protective material that is easy and fast to remove if steel has stuck to it. This would ease clean-up efforts after a mishap.

To reduce the risk of ladle breakthrough:

- A collection pit made of a refractory material covered with a bed of sand can be placed under the furnace. In case of a ladle breakthrough, melt will stream down into the pit, making it easier to collect and handle after solidification.
- Rigorous inspection routines for refractory wear assessment during and between the processed melts.
- Continuous monitoring of the temperature in the ladle wall, either by using thermal imaging cameras or by installing thermocouples. Automatic shutdown of heating at registration of a critical temperature.
- Conservative limits for relining of ladle.
- Special designed charging system assuring centering and safe filling of metallic parts into the ladle to avoid lining damage.

To reduce risks and improve conditions in case of furnace power loss:

- Investigate if the conventional cylindrical furnace design can be modified to minimize the manual work in case of such a situation. A slightly conical furnace chamber allowing easy removal of a solidified melt will be beneficial. It should also be investigated if a furnace in which a safe re-melt of a solidified melt can be done is possible to design.

12 Discussion

This chapter contains the authors' evaluation and reflection of the material presented in earlier chapters.

12.1 Technical maturity

12.1.1 Melting of LL-LLW

Melting of LL-LLW is, as stated in earlier chapters of this report, a mature technology. This treatment is performed for free release or volume reduction. Free release is achievable in many cases due to the relatively high clearance levels for long-lived nuclides.

12.1.2 Melting of LL-ILW

The ILW melting facility as described in this report is mainly based on available, mostly well known technology. This applies e.g. to remote controlled lifting and conveying devices, the use of hot-cells with manipulators, etc.

The main technical challenge is, not unexpectedly, the furnace itself. As this report has stated, experience from operation of melting furnaces for mainly LLW have shown that operational disruptions and accidents occur to an extent that they should be considered as expected.

Considering normal operation with no disturbances, it is the authors' view that a facility for melting of ILW can be operated in the way described in this report. Therefore, normal operation conditions are not considered to be critical for the technical feasibility. This does not, of course, mean that there are no challenges in its construction and design. Further studies would be needed to specify and dimension all the systems, with the hot-cell, the furnace and its docking system in particular.

However, under non-normal operation several factors may influence the feasibility of the facility. The main factors relate to loss of electric supply, ladle breakthrough as well as vapour explosions.

As shown in the risk assessment, occurrences such as loss of electric supply and other technical failures take place relatively frequently. It is not known whether it is possible to construct the furnace and auxiliary systems in a way that mitigation of the consequences of an event (mainly removal of the solidified melt) can be satisfactory performed by the use of remote equipment. In addition, unexpected occurrences are common in complex industrial facilities. This means that it will not be possible to design the systems in such a way that any type of situation can be remedied remotely.

As it is questionable to what degree personnel could perform such work in the radiological environment of the facility, the authors' view is that the technical maturity is not satisfactory at present.

12.2 Personnel safety

As has been stated in this report, there are several risks involved in the operation of a melting facility in general. For ILW, additional risks apply. This relates mainly to worker safety from a radiological point of view.

The authors' view is, based on operational experience from melting, that as long as the technology cannot secure that the risk of abnormal occurrences is very low, it is necessary to specify radiological limits for the melting operation.

In this report the main radiological parameter that has been quantified has been the ingot dose rate. This may be considered to be approximately representative for the melt from which the ingot is produced. Of the two ingot dose rate values discussed in this report, 10 mSv/h and 100 mSv/h, the former is deemed to be more reasonable. However, it should, be noted that even this value is considered high and is expected to cause technical challenges for the designers and operators of a facility.

12.3 Cost and benefit

Melting of LL-LLW is considered to be a cost effective treatment due to the possibilities to achieve free release of the metal.

While operation of an ILW melting facility would lead to volume reduction, the main characteristics of the waste would still remain, and no waste would be possible to treat for free release. The main potential benefit is therefore in the increased long term safety, and in the volume reduction of the waste.

Long term safety

The reduced surface-to-volume ratio of the melted material increases long term safety by reducing the amount of corroded material per time unit and thereby the release of radionuclides from the waste.

The effect of this on the long term safety is hard to quantify exactly, as it depends on several factors, such as geometrical shape of the original component or whether the radionuclides were distributed on the surface of the original component or as induced activity. For this reason, a detailed analysis of the long term safety has not been presented in this report.

However, it should be noted that since melting of the highest level waste types are deemed not possible, this means that no long term safety increase is achieved for this waste. Since it is this waste that is the most radiotoxic it also follows that the long term safety concerns of this part of the waste remains.

For the above reason it is likely that the long term safety is increased for certain core components and reactor internals, but not for others. This may mean that the treatment method does not decrease the need for safety barriers in the repository.

Disposal volume reduction

This report has presented meltable fractions for two values of the final ingot dose rate, 10 and 100 mSv/h, respectively. It is estimated that with a 10 mSv/h limit, approximately 85% and 72% of the LL-LILW from the BWR and PWR reference reactors respectively will be meltable after 50 years of decay. The corresponding value with a 100 mSv/h limit will be approximately 95% and 75% respectively.

Considering that the majority of the Swedish reactors are of the BWR type, this means that a majority of the Swedish core components and reactor internals could be melted after a period of decay.

It is hard to assess which impact the melting would have on the required disposal volume in the final repository. Since there is no increase in the amount of material classifiable as potentially subject to free release from operation of the facility (under the assumption that there already is a facility that could melt RPV parts for free release), the same mass of material would need to be disposed.

The volume reduction would therefore be a rather complex function of meltable fraction, the segmentation/treatment performed if no melting facility is available, the limits set by dose rate requirements on packages etc. If, for example, a disposal package only allows for a certain dose rate and/or activity content, a volume reduction treatment on a component may not lead to a volume reduction for disposal if that component is close to the limiting values.

Based on the above, it may be argued that the volume reduction potential is larger for the lower level waste, where radiological parameters and need for shielding are not as severe, while the higher activity waste probably has a lower volume reduction potential due to that radiological parameters rather than total volume may be limiting.

In order to make a quantitative assessment, it is assumed that the mass fraction of meltable waste corresponds to the volume fraction. According to SKB (1999), the volume of packaged waste for SFL-5 is approximately 10,000 m^3.

In the case of only allowing for an ingot dose rate of 10 mSv/h, it is assumed that 75%, i.e. 7,500 m^3, of this would be subject to treatment. As stated above, the volume reduction factor is hard to assess, but may for this argument be assumed to be 3. This would lead to a reduction by 5,000 m^3 of packages waste, to a total disposal volume of approximately 5,000 m^3.

For the case of 100 mSv/h ingot dose rate, which gave a meltable fraction of approximately 85% taking both reactor types into account, the corresponding calculation leads to a disposal volume of 4,300 m^3, i.e. still approximately half of the original volume.

This volume reduction is significant and reduces the cost for construction of the disposal facility.

Cost benefit

From the above, it is clear that melting of the ILW gives some advantages both regarding the long term safety and in disposal volume reduction.

However, it is at this stage hard to assess the cost benefits due to insufficient knowledge regarding the alternative of no melting facility. To a large extent this is affected by both the final volume reduction as well as the possibility to decrease the complexity of the technical barriers in the repository. Since the most radiotoxic waste is deemed not treatable it is hard to estimate if the overall barrier system may be reduced.

12.4 Alternative approaches

It is the opinion of the authors that there may be similar alternative treatment methods that may be more advantageous. One such method would be to encase ILW in molten LLW to achieve the combined advantage of increased long term safety (delayed corrosion of the encased ILW material) and the potential for total volume reduction due to radiological shielding from the encasing metal rather than of the disposal packages.

Such treatment would in principle be similar to the concept discussed in this report, but with reduced risk by melting LLW instead of ILW. This is also likely to reduce the need for decay storage.

13 Conclusions

This study has assessed the technical feasibility to construct and operate a facility for melting of LL-ILW. This has been made primarily from the view point of Studsvik's experience of operating a melting facility for LLW.

Based on operating experience and a risk assessment, the authors' conclusion is that without improvements in safety technology, mainly related to the furnace, a dose rate requirement for the melt needs to be set. This is because the need for manual labour cannot be excluded during accidents which have a relatively high risk to occur. From the view point of worker protection a 10 mSv/h limit is a reasonable estimate. However, with this limit, still not all waste can be melted.

Based on the discussion in Chapter 12, it is hard to assess the potential cost benefits from the studied treatment. While there certainly are benefits in both long term safety for the waste that is treated, the radiotoxicity and volume of the untreatable waste still remains.

For this reason, it is not clear from this study that the cost benefits justify the cost and inherent risks involved in construction and operation of a melting facility for ILW.

14 References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

Davidsson G, 2003. Handbok för riskanalys. Karlstad: Statens räddningsverk. (In Swedish.)

Grove Software, 2012. Micro Shield. Description available at http://www.radiationsoftware.com/mshield.html. Lynchburg VA: Grove Software Inc.

IAEA, 2006. Application of thermal technologies for processing of radioactive waste. IAEA-TECDOC-1527, International Atomic Energy Agency.

SKB, 1999. Deep repository for long-lived low- and intermediate-level waste. Preliminary safety assessment. SKB TR-99-28, Svensk Kärnbränslehantering AB.

SSM, 2008a. Strålsäkerhetsmyndighetens föreskrifter och allmänna råd om fysiskt skydd av kärntekniska anläggningar. Stockholm: Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority). (SSMFS 2008:12) (In Swedish.)

SSM, 2008b. The Swedish Radiation Safety Authority's regulations concerning basic provisions for the protection of workers and the general public in practices involving ionising radiation. Stockholm: Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority). (SSMFS 2008:51)

Appendix A

Process flow ILW metal treatment