Strål säkerhets myndigheten
Swedish Radiation Safety Authority

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Research

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Calculated radiological consequences of applying European clearance levels to scrap metal from the decommissioning of Swedish nuclear facilities

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SSM perspective

Background

Many practices involving radioactive substances generate materials with potential or known radioactive contamination. Clearance of materials means a decision that such materials can be released from regulatory control and used or disposed of without restrictions from a radiation protection point of view. According to regulations issued by the SSM, such decisions must be based on thorough measurements of the activity content and it must be shown that the activity content is below certain values, so called clearance levels. Clearance of metals for recycling is a well-established part of the system for management of radioactive waste in Sweden. Metals are being cleared both directly from the practices or facilities and after treatment in the waste treatment facilities in Studsvik.

In accordance with international recommendations and requirements, the SSM regulations on clearance of materials are based on the criterion that no member of the public should receive a yearly radiation dose that exceeds in the order of 10 microsieverts. In this context, workers that handle cleared materials are regarded as members of the public.

Both the clearance levels in the SSM regulations and in the permission for clearance of metallic ingots from the Studsvik melting facility are based on recommendations from the European Commission (RP 122 part 1 and RP 89, respectively). The clearance levels in the regulations will soon be changed to the values given in the new European directive on radiation protection (Directive 2013/59/Euratom). No change is foreseen concerning the recommendation RP 89.

Dismantling of nuclear power reactors in expected to generate large amounts of cleared scrap metals in Sweden in the near future. In this context, SSM has identified a need to review the applicability of the European recommendations in Sweden and to investigate if the clearance levels give a sufficient level of protection for members of the public. SSM therefore initiated the study that is presented in this report.

Results

The project has given valuable information on the current procedures for handling and treatment of scrap metals and on the possible dose consequences when applying the clearance levels of Directive 2013/59/Euratom and the recommendation RP 89.

Objective

The study indicates that the clearance levels of Directive 2013/59/Euratom give sufficient protection for people handling cleared scrap metals and by-products of metal recycling. For some gamma-emitting radionuclides, the study indicates that the clearance levels of the European Commission recommendation RP 89 do not give sufficient protection when transporting large amounts of scrap metals.

The study can serve as a basis for SSM:s continued work on regulation and supervision of clearance of materials.

Need for further research

The SSM has an interest in evaluating the impact of its regulations. To this end, it would be of interest to investigate the actual dose consequences from the recycle and reuse of cleared materials.

Project information

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This report concerns a study which has been conducted for the Swedish Radiation Safety Authority, SSM. The conclusions and viewpoints presented in the report are those of the author/authors and do not necessarily coincide with those of the SSM.

SSM 2018:08

Calculated radiological consequences of applying European clearance levels to scrap metal from the decommissioning of Swedish nuclear facilities

Summary

The aim of this project is to identify whether the clearance levels in the European Basic Safety Standards Directive (2013/59/Euratom) and the European Commission recommendation RP 89 offer a suitable level of protection for the public in relation to the recycling of cleared scrap metal from nuclear installations. This has been carried out using a combination of stakeholder interviews and a literature review to examine the suitability of the exposure scenarios in RP 117 (that forms the basis for RP 89) for application in Sweden. The normalised dose calculations were then adjusted to reflect the process chain in Sweden, and the most restrictive doses used to define clearance levels that could be compared with those in directive 2013/59/Euratom and RP 89.

The results show that the rounded clearance levels derived are equal to or higher than the general clearance levels in directive 2013/59/Euratom for all radionuclides considered in this study. This means that, despite the differences in many of the parameters applied in RP 117 and this study, application of the BSS clearance levels would limit the exposure of the Swedish public to below the order of 10 microsieverts per year.

Comparison of the rounded clearance levels derived in this study with the levels recommended in RP 89 shows a more variable situation. The rounded clearance levels are the same for 24 of the radionuclides, while those derived for Sweden are higher for 5 radionuclides and lower for 10 radionuclides, for example $^{110m+}$Ag, ^{60}Co and $^{125+}$Sb. The reason for the difference for these 3 radionuclides is that the time for transporting cleared scrap is considered to be longer in Sweden than is assumed in RP 117.

Sammanfattning

Detta projekt syftar till att utreda om de friklassningsnivåer som anges i EU:s strålskyddsdirektiv (2013/59/Euratom) och i EU-kommissionens rekommendation RP 89 ger ett tillräckligt skydd för allmänheten mot skadlig verkan av strålning vid friklassning av metallskrot från kärntekniska anläggningar i Sverige. Utredningen baseras på en kombination av intervjuer med berörda parter och en litteraturstudie för att undersöka hur de scenarier för exponering som anges i RP 117 (som ligger till grund för värdena i RP 89) förhåller sig till hur metallskrot processas i Sverige. Beräkningarna i RP 117 har därefter justerats för att motsvara processerna i Sverige och det mest restriktiva scenariot har använts för att beräkna friklassningsnivåer, vilka därefter har jämförts med friklassningsnivåerna i direktiv 2013/59/Euratom och RP 89.

Jämförelsen visar att de beräknade och avrundade friklassningsnivåerna är lika med eller högre än de generella friklassningsnivåer som anges i direktiv 2013/59/Euratom för alla radionuklider som inkluderats i denna studie. Detta innebär att, även om många av de ingående parametrarna skiljer sig åt, så leder en tillämpning av friklassningsnivåerna i direktiv 2013/59/Euratom till en begränsning av exponeringen av allmänheten i Sverige till nivåer under cirka 10 mikrosievert per år.

Jämförelsen av de beräknade friklassningsnivåerna med de nivåer som rekommenderas i RP 89 visar en mer varierande bild. De beräknade och avrundade friklassningsnivåerna är lika för 24 av de ingående radionukliderna, högre för 5 av radionukliderna och lägre för 10 av radionukliderna, till exempel $^{110m+}$Ag, ^{60}Co and $^{125+}$Sb. Skillnaden för dessa tre radionuklider beror på att transporttiden i Sverige bedöms vara längre än vad som antas i RP 117.

Content

1. Introduction

1.1. Clearance and clearance levels

Clearance levels define the maximum activity concentrations (Bq/g) or surface activity concentrations (Bq/cm^2) of a specified radionuclide in a material that can be released from regulatory control. Clearance is important for the nuclear industry, particularly during the decommissioning of reactor sites, and prevents the unnecessary disposal of recyclable materials as radioactive wastes. The clearance procedure must ensure that "the effective dose expected to be incurred by a member of the public… is of the order of 10 μSv or less in a year" (BSS 2013). Here, "the public" includes non-radiological workers.

General clearance levels are usually derived by assessing the potential dose received by the most exposed member of the public from 1 Bq/g of a given radionuclide in a cleared material in realistic but slightly pessimistic scenarios. The scenario that leads to the highest dose is used to identify the lowest activity concentration of the radionuclide in the material that could lead to a dose of 10 μSv year^{-1}. For simplicity, the activity concentration calculated is then rounded up or down to obtain the clearance level; if the calculated value lies between 3 x 10^x and 3 x 10^{x+1}, then the rounded value is 1 x 10^{x+1} (RP 89). In order to clear a material containing more than one radionuclide, the sum of each activity concentration divided by its clearance level must not exceed a value of one.

International studies by expert groups have defined exposure scenarios for a range of different materials and derived general clearance levels. The European Basic Safety Standards (BSS 2013) adopted the clearance levels derived for solid materials in IAEA (2005), and these will now be implemented in Sweden. They will replace the current clearance levels for materials given in SSMFS 2011:2. The IAEA (2005) clearance levels were derived for application to all solid materials and the scenarios used include aspects of metal recycling (Table 1). However, as the scenarios are generic, the assumptions are not tailored to the recycling of cleared scrap metal from nuclear installations.

Table 1 Scenarios applied in IAEA (2005) and exposure pathways considered

Scenario	External exposure	Inhalation	Ingestion of contaminated material	Ingestion of drinking water	Ingestion of food grown on contaminated land	Ingestion of fish from contaminated water
WL – Worker on landfill or in other facility (other than foundry)	X	X	X			
WF – Worker in foundry	X	X	X			
WO – Other worker (e.g. truck driver)	X					
RL-C – Resident (1-2 yr old child) near landfill or other facility		X			X	
RL-A – Resident (adult) near landfill or other facility		X			X	
RF – Resident (1-2 yr old child) near foundry		X				
RH – Resident (adult) in house constructed of contaminated material	X					
RP – Resident (1-2 yr old child) near public place constructed with contaminated material	X	X	X			
RW-C -– Resident (1-2 yr old child) using water from private well or consuming fish from contaminated river				X	X	X
RW-A -– Resident (adult) using water from private well or consuming fish from contaminated river				X	X	X

Specific European clearance levels for recycling scrap metals from nuclear installations have, however, been derived in RP117 and recommended in RP89. BSS (2013) states that "***Specific clearance levels, as well as corresponding Community guidance, remain important tools for the management of large volumes of materials arising from the dismantling of authorised facilities"***, and lists RP89 in the relevant community guidance. Therefore both the scenarios developed in RP117 and the clearance levels recommended in RP89 for the clearance of scrap metals remain relevant for decommissioning projects. The wide range of scenarios applied in RP117 are given in Table 2. They take into account the exposure of (non radiological) workers during the transport, storage, recycling and processing of steel, copper and aluminium, and disposal of waste products, and the exposure of the public to products produced from the metal or slag or due to homes being built on landfills containing the slag or dust (see Table 2). It is therefore the most comprehensive analysis of potential public exposure scenarios following the clearance of scrap metals in Europe.

Table 2 Exposure scenarios applied to individuals in RP117

Scenario	Steel	Copper	Aluminium
Scrap yard	External (transport) Inhalation (cutting)	External (transport)	External (transport)
Foundry	External (heap) Inhalation of dust (melting) Ingestion of dust (melting)	External (heap) Inhalation of dust (melting) Ingestion of dust (melting)	External (heap) Inhalation of dust (melting) Ingestion of dust (melting)
Atmospheric emission	Combination of inhalation, ingestion and external exposure (member of the public)	Combination of inhalation, ingestion and external exposure (member of the public)	Combination of inhalation, ingestion and external exposure (member of the public)
Treatment of by-products and purification treatment		External (slag processing, electro refining) Inhalation (dust compacting, zinc recovery, slag processing)	External (slag processing) Inhalation (slag processing)
Post refining	External (manufacture) Inhalation of dust (metal processing)	Inhalation (manufacture)	Inhalation (manufacture)
Use of products (occupational)	External exposure from each of the following products: Machine Kitchen Process vessel Boat	External exposure from each of the following products: Brass laboratory object Large decoration Brass musical instrument	External exposure from each of the following products: Office furniture Fishing boat Office ceiling
Use of products (domestic)	External exposure from the following: Reinforcement bars Radiator	External exposure from a brass kitchen fitting Ingestion of pig meat	External exposure from the following Radiator Car engine Ingestion of saucepan particles
Disposal of by-products	Landfill workers: External exposure Inhalation of dust Ingestion of dust Residential (landfill public): Combined external exposure, inhalation of dust, and ingestion of soil and food	Landfill workers: Skin contamination External exposure Inhalation of dust Ingestion of dust Residential (landfill public): Combined external exposure, inhalation of dust, and ingestion of soil and food	Landfill workers: Skin contamination External exposure Inhalation of dust Ingestion of dust Residential (landfill public): Combined external exposure, inhalation of dust, and ingestion of soil and food
Use of by-products	Football field made of slag: Inhalation player Inhalation spectator	Football field made of slag: Inhalation player Inhalation spectator	Concrete ceiling made of slag (external exposure)

1.2. Difference between SSMFS 2011:2, BSS (2013) and RP89 clearance levels

Table 3 compares the clearance levels for selected radionuclides in RP89, BSS (2013) and SSMFS 2011:2. Comparison of the new BSS (2013) clearance levels with those in SSMFS 2011:2 shows a variable pattern. For 22 of the 37 nuclides listed, the clearance levels are the same, for 7 the clearance level will decrease with the implementation of the new BSS, i.e. be more restrictive, while for 7 others the clearance level will become less restrictive. Note that ^{108m}Ag is not listed in the clearance levels of BSS (2013). However, for all the radionuclides listed in Table 3 except ^{40}K, the clearance levels in RP89 are higher or equal to those in BSS (2013) and SSMFS 2011:2, suggesting that both sets of general clearance levels are broadly conservative for scrap metal recycling. One of the reasons for this is that the RP117 scenarios (on which RP89 is based) assume that the cleared metals are mixed with other metals to varying degrees. No dilution is assumed in

IAEA (2005) except in scenario RP, which considers children playing in a public place made partially from cleared material. ^{40}K is treated as a naturally occurring radionuclide in BSS (2013), and its clearance level was derived on the basis of background soil concentrations rather than through scenario analysis. In IAEA (2005), ^{40}K was included in both the anthropogenic and naturally-occurring radionuclide assessments. The clearance level derived in the anthropogenic assessment was 1 Bq/g, which is consistent with RP89 and SSMFS 2011:2. It should also be noted that some of the clearance levels derived in RP117 were increased to 1 Bq/g in RP89 because the radionuclide was considered to be present in such small quantities in scrap cleared from nuclear reactors that the overall activity considered in the RP117 scenarios was overestimated. These radionuclides are marked with an asterisk in Table 3.

However, all dose assessments using scenario analysis are sensitive to the parameters and assumptions applied. These relate to working practices, the mixing of cleared scrap with other scrap or metal feedstock at the recycling plants, the distribution of the radionuclides between the melt, slag and dust during smelting, and human behaviour patterns. Some of these data, such as working practices, level of dilution and uses of materials can vary between countries, while other data such as the radionuclide distribution during melting data can be periodically improved. It is therefore possible that the scenarios and assumptions applied in RP117 are not consistent with practice in Sweden and/or the current best available data.

1.3. Aim of the project

The aim of this project is to identify whether the BSS (2013) and RP89 clearance levels offer a suitable level of protection for the public in relation to the recycling of cleared scrap metal from nuclear installations. This has been carried out using a combination of stakeholder interviews and a literature review to examine the suitability of the assumptions applied in the exposure scenarios of RP117 for application in Sweden. The normalised dose calculations were then adjusted to reflect the process chain in Sweden, and the most restrictive doses used to define rounded clearance levels that could be compared with those in BSS (2013) and RP89.

Table 3 Comparison of the clearance levels in RP89, BSS (2013) and SSMFS 2011:2 for selected radionuclides

	Clearance levels (Bq/g)			RP89/BSS	RP89/ SSMFS 2011:2	BSS/ SSMFS 2011:2
Nuclide	**RP89**	**BSS (2013)**	**SSMFS 2011:2**			
Ag-108m+	1	not given	0.1	-	10	-
Ag-110m+	1	0.1	0.1	10	10	1
Am-241	1*	0.1	0.1	10	10	1
C-14	100	1	10	100	10	0.1
Cd-109+	10	1	10	10	1	0.1
Ce-144+	10	10	10	1	1	1
Cm-244	1	1	0.1	1	10	10
Co-57	10	1	1	10	10	1
Co-58	1	1	0.1	1	10	10
Co-60	1	0.1	0.1	10	10	1
Cs-134	1*	0.1	0.1	10	10	1
Cs-137+	1	0.1	1	10	1	0.1
Eu-152	1	0.1	0.1	10	10	1
Eu-154	1	0.1	0.1	10	10	1
Eu-155	10	1	10	10	1	0.1
Fe-55	10000	1000	100	10	100	10
H-3	1000	100	100	10	10	1
K-40	1	10§	1	0.1	1	10
Mn-54	1	0.1	0.1	10	10	1
Na-22	1*	0.1	0.1	10	10	1
Nb-94	1	0.1	0.1	10	10	1
Ni-59	10000	100	100	100	100	1
Ni-63	10000	100	100	100	100	1
Pu-238	1*	0.1	0.1	10	10	1
Pu-239	1*	0.1	0.1	10	10	1
Pu-240	1*	0.1	0.1	10	10	1
Pu-241	10	10	1	1	10	10
Ru-106+	1	0.1	1	10	1	0.1
Sb-124	1	1	0.1	1	10	10
Sb-125+	10	0.1	1	100	10	0.1
Sc-46	1*	0.1	0.1	10	10	1
Sn-113+	1	1	1	1	1	1
Sr-90+	10	1	1	10	10	1
Tc-99	100	1	1	100	100	1
U-234	1	1§	1	1	1	1
U-235+	1	1§	1	1	1	1
U-238+	1	1§	1	1	1	1
Zn-65	1	0.1	1	10	1	0.1
Zr-95+	1	1	0.1	1	10	10

+ short-lived daughters are included

§Clearance levels for naturally occurring radionuclides were derived using a different process in IAEA (2005), based on activities in natural soils

*increased to 1 Bq/g due to the small quantities expected in scrap metal

2. Methods

2.1. Interviews with stakeholders

In order to evaluate whether the dose assessment scenarios and input data applied in RP117 are relevant for Sweden, it is necessary to understand the procedures applied at relevant facilities in Sweden. Therefore, interviews were carried out with:

- Nuclear facilities where metal is cleared or will be cleared in the near future
- Recycling centres, where scrap metal is received, sorted, processed and then sent to smelting facilities
- Smelting facilities for steel, copper and aluminium, where the scrap is converted into different grades of metal

At all stages, the material flow for the following types of scrap were considered: steel (divided into stainless steel and carbon steel; though there are many more classes of steel, depending on grade, special alloys etc.), copper and aluminium. A key issue was to establish the amounts of cleared scrap compared to other materials handled or used at each facility, in order to establish the level of mixing, or dilution. Note that the Swedish fuel fabrication plant was not contacted.

2.1.1. Nuclear facilities

SSM provided the details of a contact person at each nuclear power facility in Sweden (Barsebäck, Forsmark, Oskarshamn, Ringhals), Cyclife (formerly Studsvik Nuclear), which has a melting facility for treatment of scrap from nuclear sites and minimising waste volumes, and SVAFO, which is responsible for the decommissioning of the R2 research reactors and maintenance of Ågesta, a shut-down nuclear power facility. A list of questions was compiled and sent to each of these contacts, and then a telephone interview was conducted to elaborate on the answers.

The questions examined:

- The amounts of iron/steel, copper and aluminium cleared per year
- The radionuclide concentrations reported during the clearance procedure
- The measurement process used, and the method for estimating concentrations of nuclides that are difficult to measure
- The handling of metals during the clearance process and mass of scrap metal in each batch taken to the recycling centre
- The recycling centres used and the rationale for the selection of the site(s)

2.1.2. Recycling centres

The interviews with the nuclear facilities suggested that the recycling centre selected to receive scrap metal depends on the market situation. However, two companies were identified as the main receivers of cleared metal. Although both of these companies have several centres distributed around Sweden, one company mainly sends metals to one of their centres. Telephone interviews were held with the operations managers (one at company level, one at a recycling centre) and the following questions were discussed:

- The mass of material processed at each centre
- Whether incoming batches are kept separate or mixed with other material

- The size of storage facilities for incoming scrap metal, and the turnover times for the material
- Handling/treatment of scrap metal
- Waste products arising from the treatment processes
- Transport methods
- The amount of metal in each batch sent out to buyers.
- The principle users of scrap metals.

2.1.3. Smelting Facilities

The recycling centres identified a number of smelting facilities that purchase steel, copper and aluminium scrap to produce new materials. Telephone interviews were therefore conducted with the operations managers at these facilities, and the information received was supplemented with information from the annual environmental reports (miljörapporter) to the licencing authorities. The questions addressed were:

- The amount of scrap material used
- Capacity of the storage facilities with regard to scrap metal and the turnover time of metal in storage
- Treatment of incoming scrap
- The total amount of product per year
- Maximum and minimum rations of scrap used in relation to primary material in a melt
- Types and amounts of waste products arising
- Disposal or reuse of the waste products
- Areas of use for the metal produced

The facilities contacted included:

- Ore-based steelworks
- Carbon-steel foundries
- Stainless steel foundries
- Copper smelters
- Aluminium smelters

2.2. Evaluation of the RP117 scenarios and parameters for application to Sweden

The clearance levels in RP89 directly apply to metal recycling and are based on the scenarios developed in RP117. The scenarios are based on a number of input data and assumptions relating to:

- The amounts of scrap cleared each year and dilution of cleared scrap with other material in each stage of processing through to product use and waste management
- The use of products and by-products, and waste management approach
- The time spent on each activity
- The proximity and geometry of the material, and shielding
- Dust concentrations in the air and breathing rates
- Rates of inadvertent dust ingestion
- Redistribution of the radionuclides into the metal, slag and dust fractions during smelting

- Change in concentration of radionuclides that redistribute into the slag and dust fractions, due to the smaller matrix mass

First, the material flow assumptions in RP89/117 were reviewed and the most restrictive scenario for each radionuclide in each metal (steel, copper, aluminium), and for all three metals, was identified. The most restrictive scenarios and the assumptions applied were then discussed. The limiting scenarios in RP117 were compared with those in an equivalent study from the USA (NUREG 1640) both in terms of exposure pathways and numerical differences in the doses calculated.

The information from the stakeholder interviews was used to identify where the RP117 scenarios or material flow assumptions are consistent with the situation in Sweden. NUREG 1640 (NUREG, 2003) was also used to support the critical evaluation of the parameters in the most restrictive scenarios, as was US EPA (2001), a similar but slightly earlier study from the USA. The numerical differences between the maximum normalised dose rates calculated in RP117 and NUREG 1640 were also examined to see the impact of the different scenarios or parameters included on the eventual clearance level derived. Differences in the redistribution data applied in RP117 and NUREG 1640, to describe radionuclide redistribution into the metal, slag and dust fractions during smelting, were identified for further consideration. The dose coefficients applied in RP117 were compared with the most recent dose coefficients (IAEA 2014), to identify where the data can be improved. Finally, a scrap cutting scenario was defined for Sweden, taking a different approach from that used in RP117. This was a better representation of Swedish practice and allowed the calculation of the doses received from all radionuclides via both inhalation and ingestion.

Conversion factors were identified to adjust the RP117 dose rates in each scenario to reflect the parameters identified for Sweden. This allowed both the most restrictive pathway and the actual maximum dose rate to change, in reflection of Swedish practice.

2.3. Calculation of clearance levels and comparison with BSS (2013) and RP89

The dose rates calculated for Sweden were converted into 10 μSv/year clearance levels for the radionuclides identified as relevant for Swedish nuclear facilities. The most restrictive clearance levels were then rounded up or down according to the process described in Section 1.1 and compared with the new BSS (2013) clearance levels. The aim here was to assess whether the BSS clearance levels are adequate for the recycling of scrap metal from Swedish nuclear facilities. The rounded clearance levels were also compared with those in RP89 to examine whether the RP89 clearance levels are adequate for these materials in Sweden.

3. Handling of materials in Sweden

3.1. Nuclear facilities

3.1.1. Mass of steel, copper and aluminium cleared

At the moment, relatively small amounts of metal are cleared at nuclear facilities in Sweden (Table 4) but these amounts will increase as decommissioning projects progress. Although preparation is underway for the dismantling of the power station at Barsebäck, no estimate of the amount of potentially clearable metal at the site was available. Also, materials are not currently being cleared at the site. Similar amounts of metal are cleared annually at Forsmark and Ringhals; generally about 50 tonnes. However, the amount varies depending on the types of maintenance projects being carried out, and can be much higher if large components are cleared. For example, at Ringhals, clearance of 6 turbine rotors (55 tonnes each) led to clearance of more than 300 tonnes in one year. At Forsmark, the maximum amount of material cleared in one year was around 250 tonnes. At Oskarshamn, the process for clearing metals is being developed, but there are no estimates yet of the amounts that will be cleared.

SVAFO clears about 36 tonnes of metal per year and send larger components directly to Cyclife for melting and subsequent clearance. Steel accounts for between 75% and 95% of the total amounts of metal cleared by SVAFO and is mainly carbon steel. The metals arise from decommissioning at Studsvik (R2), which is expected to continue for several years. The decommissioning of the reactor at Ågesta is planned to begin in about 2020, and this is expected to lead to the clearance of a similar amount of metal annually.

Studsvik clear about 2500 tonnes of material per year. Material cleared from Studsvik can be cleared by two different routes:

- According to SSMFS 2011:2, these ingots are sold directly to any scrap metal broker for any use (general clearance)
- According to RP89; but with a specified minimum level of dilution during remelting at an external foundry (conditional clearance)

The main metal being cleared is steel. Copper accounts for about between 3 % and 13 % of the total metal currently cleared from the nuclear facilities interviewed, and is mainly from copper cable. Aluminium accounts for under 10 % of the total amount of cleared metal (between 3 and 9 %). Studsvik also clears small amounts of other metals: lead (from lead bricks used for shielding, 10-50 tonnes per year), brass and titanium (relatively small masses).

Table 4 Mass of metals cleared annually from nuclear facilities in Sweden

	Ringhals	Oskarshamn	Forsmark	Barsebäck	SVAFO	Cyclife (see report)
	amount of cleared metal tonnes/year					
Total	Min ca 35 (2009, 2013). Max >360 (2014) (6 st turbine rotors ~60 tonnes each)	Very little to date. Large backlog, amount unknown	50 average. Max 253 (2006) Min 17 (2003)	None today. Estimates of amounts from decommissioning being made, but not yet completed.	36	ca 2650
Carbon steel			95%		26.5	95 %
Stainless Steel			incl in above		1.5	incl in above
Aluminium			2%		3.1	4 %
Copper			3%		0.9	
Copper cables					4	2 %
Lead						small amounts
Brass						small amounts
Titanium						small amounts

3.1.2. Clearance procedure

The nuclear facilities provided information on the processes and measurement procedures used to determine concentrations of radionuclides during clearance. Larger components may be cut up before the clearance process (information from one power station), although very large components (e.g. turbine rotors) can be cleared in one piece and sent by special transport to recycling facilities. At all nuclear facilities, surface contamination is measured before the metals go for clearance. Swab tests are carried out to check for alpha-contamination, and if any alpha-contamination is detected, the material is sent for decontamination. The risk of the material being contaminated on the inside is assessed, since inner contamination cannot be measured because of self-shielding. If inner contamination is likely, components are not cleared.

Clearance is usually carried out by packing the material in large boxes with a standard geometry, ca 1 m^3. The detector is calibrated according to the box geometry, the material of the walls of the box, mass of the contents and the degree to which the box is filled. Special measurements of specific areas of the material are carried out if there is reason to suspect that local activity concentrations might be higher. At some other power stations, and for larger components, the geometry of each batch/component is unique and so the detector is calibrated for the geometry of every batch of material. The In Situ Object Counting Systems (ISOCS) calibration software from Canberra and ISOTOPIC calibration software from Ortec are used at the facilities.

The radionuclide contamination is likely to consist of the most common fission and activation products in the reactors, particularly those associated with materials that corrode. However, some of these radionuclides are difficult to measure by gamma spectrometry, or may often be present at very low activity concentrations. Therefore, each nuclear facility has to determine the relative activity concentrations of radionuclides that are likely to be present to produce a radionuclide vector for each reactor. These allow the activity concentrations of the radionuclides that are difficult to

measure to be estimated from those that are easier to measure and present at a relatively high activity concentration, such as ^{60}Co (Appendix A). Radionuclides that make a negligible contribution to the overall activity can be excluded from the vector. At Forsmark, the vectors are based on analysis and modelling of the composition of reactor water and the radionuclides that have an estimated activity concentration >1% of the clearance level are included. At SVAFO, the radionuclide vector is specific to the facility being decommissioned. At Cyclife, the vector is based on the radionuclides given in customer declarations, and again only those with a concentration >1% of the clearance level are included.

Therefore, each facility has established a list of radionuclides for each reactor that are considered in the clearance process, either by direct measurement or via a radionuclide vector. Gamma spectrometry is used to determine the activity concentration of a number of these radionuclides, and the others are estimated. Often, only ^{60}Co can be detected and then the minimum detectable activities of a number of other radionuclides may be included to demonstrate compliance with the clearance level, depending on the site and the relative importance of ^{60}Co in the vector.

Four of the companies interviewed (Forsmark, Oskarshamn, Ringhals, Svafo (R2)) provided a list of the radionuclides included in their clearance reports, and stated whether each radionuclide was determined or estimated using their facility-specific radionuclide vector. The full list is given in Appendix A, together with information on the radionuclide minimum detectable activities included in the clearance process. In order to identify the most important isotopes with respect to clearance of metals from Swedish nuclear sites and to exclude those that will undergo extensive decay after clearance but before leaving the nuclear site, the following criteria were applied:

1. The concentration of the radionuclide is determined directly by at least one organisation, or included in the radionuclide vector of a minimum of two
2. The half-life of the radionuclide is greater than 50 days

^{59}Ni, ^{234}U and ^{241}Pu did not fulfil these criteria but were considered to be of sufficient importance to be included. Equally, ^{133}Ba did fulfil the criteria, but is not included in RP117 or the current Swedish clearance levels (SSMFS 2011:2) and so was not considered. The list of radionuclides identified for this study is given in Table 5, together with their half-lives.

After clearance, metal scrap is sent to the recycling centre of the nuclear facility, where the material is sorted into different types (steel, copper and aluminium). Sorting and storage can occur in a number of stages and cleared metals can be mixed with other metal scrap (from non-regulated activities) from the nuclear facility. For example, at Forsmark, the different streams of scrap are mixed at Forsmark's own recycling centre. As a result, only about 25% of the metal in each batch of scrap sent to the external recycling centre is cleared scrap. The containers in which the scrap metal is held vary in size between the different facilities, between 0.5 tonne and 5 tonne containers (22 m^3). Cleared metals are stored at the nuclear facility for a few (1-4) months, before transport to the external recycling centres.

Scrap is sent to external recycling centres in batches, and the timing of the transport and the choice of centre is dependent on the market situation for scrap. Transport to the external recycling facilities is usually by truck, with the material in 14 m^3 and 22 m^3 containers (5 tonnes). Three 5 ton containers can be transported on one truck, giving a total of up to 15 tonnes per transport.

Some cleared materials may be sent to a hazardous waste disposal facility after clearance, because the content of hazardous materials (e.g. cadmium, lead, asphalt, arsenic, thallium) leads to their classification as hazardous materials.

Table 5 Radionuclides selected as relevant for Swedish decommissioning programmes

Nuclide	Half-life (years)
Ag-108m	127
Ag-110m	0.684
Am-241	432
C-14	5730
Cd-109	1.27
Ce-144	0.779
Cm-244	18.1
Co-57	0.742
Co-58	0.194
Co-60	5.27
Cs-134	2.01
Cs-137	30
Eu-152	13.5
Eu-154	8.59
Eu-155	4.96
Fe-55	2.68
H-3	12.3
K-40	1.28E+09
Mn54	0.855
Na-22	2.6
Nb-94	20300
Ni-59	75000
Ni-63	96
Pu-238	87.4
Pu-239	24100
Pu-240	6560
Pu-241	14.4
Ru-106	1.02
Sb-124	0.165
Sb125	2.76
Sc-46	0.23
Sn-113	0.315
Sr-90	28.1
Tc-99	214000
U-234	245000
U-235	7.04E+08
U-238	4.47E+09
Zn-65	0.668
Zr-95	0.175

3.2. Recycling centres

Information was received from two major recycling companies (Table 6), while a third chose not to provide information for this study. Recycling centres in Sweden vary in size and process between 20 000 and 130 000 tonnes of scrap metal per year. There is constant stream of material through the facility and incoming material is treated more or less directly, so the average turnover time of scrap at the recycling facility is about 30 days. Incoming scrap is first sorted into different types and grades of metal using a variety of methods. There is a large number of metal grades, for example, there are about 20 grades for iron/steel. Some large metal components can be sorted directly, while many other items have to be cut up since many potential users of scrap have a maximum size that they accept. One recycling company clips the scrap using large shears to avoid sawing and the associated production of dust. During the sorting procedure, scrap from different sources is mixed together so that the material in an incoming batch seldom remains together. Personnel work full time with the sorting and treatment of scrap.

Cleared iron/steel scrap can also be treated and sorted using shredders or hammer mills. These fragment and automatically separate the material into different fractions; a magnetic fraction, a non-magnetic fraction, fines (a sand-like material) and coarse fluff (mixed material). The most relevant fractions for this study are the magnetic and non-magnetic fractions. The fluff fraction is sent for incineration and the fines fraction is used often for construction purposes (for example in landfills). The magnetic fraction is sent mainly to Swedish steelworks. Various techniques are being investigated and implemented to improve the quality of the ferrous and non-ferrous scrap, and to improve the degree of recovery from shredders and mills (Jernkontoret, 2012). The non-magnetic fraction is sent to various types of facility for refining, depending on the price. Research is also being carried out on improving the efficiency of the recycling of non-ferrous metals (mainly aluminium and copper). Shredders and hammer mills create dusty environments, and a wet-scrubber is used to remove dust from the air. The sludge from the wet scrubber is disposed of in a landfill. Copper and aluminium scrap is not fragmented, it is sorted and if necessary clipped or sawn into smaller pieces.

When recycling copper cables, stripping of the cables or granulation of cables with small diameter, to remove the plastic covering, is carried out at the recycling facility.

Once sorted, the scrap metal is sent out as soon as possible in loads of varying sizes; if transport is by road, 30-35 tonnes/load and if transport is by boat (export of scrap) 2 000-20 000 tonnes/load. Turnover times for steel scrap are shorter than for copper and aluminium, as it takes less time to accumulate at load for transport, but storage times are variable.

Table 6 Information from recycling centres

	Turnover time for scrap	**Scrap processed per year (tonnes)**		**Batch size transported smelters/ steelworks (ton)**	**Transport metod**	**By-products**
Company 1	30 days	130 000	large	25-5000 ton	truck or boat	
		20 000	small	30 - 35 ton	truck (within Sweden)	
Company 2	max 30 days, average 1 week.	48 000	refers to only one facility	2000 ton	boat (export)	Fluff (incineration)
				30 ton	truck (within Sweden)	Fine fraction (construction)
						Dust from (hammer mill scrubbers) - landfilling

3.3. Users of scrap metals

Recycling of scrap does not meet the current demand for metals. At present, scrap recycling meets about 30% of the global steel demand and 40 % of the steel demand in Sweden. The proportion of recycled steel is expected to increase in the coming years, and has been projected to 50 % globally in 2050 (Jernkontoret[1]).

In Sweden a total of about 4.5 million tonnes of raw steel are produced per year (Jernkontorets[2]). This generates about 2 million tonnes of by-products, of which about 75 % are reused internally or sold, and about 25 % are disposed of as waste (for example, in landfills). The main waste products are slag and dust and sludge from flue-gas treatment. About half of the slag produced is from blast furnaces (ore-based production) and half is metallurgical slag. Slag is partly returned to the steel production process. It may also be treated for the extraction of iron (returned to the steel making process) and other metals, after which it is disposed of, for example in a landfill, or used for other purposes, for example as a construction material as aggregate or as an additive to cement. Flue gas dusts and sludges may be disposed of as hazardous waste, or may be further refined for the extraction of metals. Zinc, chromium, nickel and iron are extracted from dusts.

3.3.1. Steel works

In Sweden, iron and steel is produced in thirteen steelworks and information was obtained from eight of these; two are ore-based with a small scrap component, six are based largely on the use of steel scrap (Table 7). One of the remaining facilities uses a different procedure (similar to the ore-based process) and did not provide information for this study.

Table 7 Swedish steel works

Company	Steel production tonne/year	Scrap used tonne/year
Ore based steelworks		
1	1 659 000	90 000
2	990 000	14 000
Other steelworks/foundries		
3	360 000	360 000
4	500 000	330 000
5	6 461	6 193
6	213 555	217 396*
7	12 300	7100
8	2500	~2000

* only 53% is scrap purchased from external sources.

The amount of scrap used as a fraction of the total amount of steel produced varies. At the ore-based steelworks, only a small proportion of the total production is scrap-based. At the other steelworks and foundries, the amount of scrap used varies between about 60% and 100% of the total production. The proportion of scrap used is not dependent on the total amount of steel processed; there are both small and large steelworks that are entirely scrap-based and large and small steelworks where the production is about 60% based on scrap.

[1] Jernkontoret (2012). Stålkretsloppet, ett Mistrafinansierat miljöforskningsprogram. Slutrapport 2004-2012. Järnkontorets Forskning, Rapport D852.
[2] www.jernkontoret.se/sv/stalindustrin/tillverkning-anvandning-atervinning

Ore based steelworks

Ore based steelworks produce steel from iron-ore pellets. Pig-iron is produced in blast furnaces from the iron-ore pellets. Steel is then produced from the pig iron in an oxygen converter where the carbon content is reduced. In Sweden an LD-converter is used. Scrap is added to the pig iron in the LD-converter, partly to control the temperature. A large amount of the scrap used is waste from the steelworks (misshapen steel forms, or material which is cut off from steel forms), and is therefore primary material). However, external scrap steel is also bought in. The amount of externally sourced scrap steel is between 1.5% and 5.5% of the total amount of raw steel produced.

The waste products from the LD-process are slag and dust/sludges from flue gas scrubbers (see Table 8). About 1 ton of slag is produced for every ton of raw steel. A large amount of the slag is returned to the process (for example to the blast furnaces). Some slag is used for construction purposes, for example in the steelwork's landfill. About 0.2 tonnes of sludges/dust from scrubbers are produced per ton of raw steel. Of this amount, about 75% is returned to the process and the rest is disposed of in a landfill. A number of products are derived from slags and dusts at the steelworks, mainly ballast and construction materials, but also a number of different metals, used, for example, in the electronic industry.

Steel foundries

Detailed interviews have been conducted with two different types of foundry; a foundry producing carbon steel, and a stainless steel works. Some information has also been provided by a number of other foundries.

The carbon steel foundry produces several different grades of steel and specialist products, using an electric arc furnace. The foundry is based on the use of 100 % scrap products, though some of the scrap comes from the primary industry. The incoming scrap is sorted into different classes on arrival but, as scrap is delivered from the recycling facilities in a ready-to-use form, very little treatment is required. The store for scrap has a capacity of about 10 000 tonnes, equivalent to 1-2 weeks use, and full time personnel are employed with the scrap storage and treatment. About 360 000 tonnes of scrap is processed to make steel per year. For every ton of steel produced here, about 100 kg slag is produced and sold, mainly for use in asphalt production (Table 8). About 1.2 kg of dust (per ton steel product) from scrubbers is sent for refining of zinc. Mill scale (1 kg per ton steel produced) has a high iron content and is reused in steel production.

The second foundry interviewed produces about 500 000 tonnes of stainless steel per year in an arc furnace. Scrap steel constitutes about 65 % of the total amount of raw steel used. Some products can be produced almost completely from scrap, with only some addition of nickel and chromium to achieve the correct composition. Incoming scrap is stored on average for two weeks, although some special types of scrap can be stored for longer. The maximum capacity in the store is 30 000- 50 000 tonnes. There is very little treatment of scrap at the foundry, though some scrap needs to be cut up into smaller pieces. Full time personnel are employed with the scrap storage and treatment. The main waste products are slag and dust/sludges from flue gas scrubbers. 130 000-140 000 tonnes of slag are sent for metal extraction before landfilling the residue (Table 8). Flue gas dusts/sludges are sent for zinc extraction within Sweden.

Waste products from the secondary process of zinc extraction (plasma reduction smelting) from flue gas dusts/sludges include slag and further dusts/sludges. The slag is used as a construction material (road construction) and the dust is sent to Spain for further refining of metals (Waeltz process).

Electric arc furnaces range in capacity from a few tonnes to as many as 400 tonnes[3]. Many furnaces have a capacity in the range 40-110 tonnes[4].

[3] http://infohouse.p2ric.org/ref/10/09047.pdf
[4] http://www.abpinduction.com/en/**steel**-plants/steel-melting/arc-melting/arc-furnace/

3.3.2. Copper smelters

Globally, about 34% of copper production is based on reuse of scrap metal. In Sweden, copper is mainly produced from mineral concentrates from ores mined in Sweden. However, other materials are also used, including scrap metal. Lead is also produced at the copper smelter and gold, silver, tellurium, platinum, selenium, nickel and zinc are also produced as by-products. Over 200 000 tonnes of copper are produced per year (Boliden[5], Boliden[6]), about 30% of which comes from the recycling of scrap metal (Boliden[7]) (Table 8).

There are other users of copper scrap in Sweden, for example copper scrap is used in the production of brass, which is then used for production of components in industry, vehicles, buildings and electronics/telecommunications. The brass smelter interviewed has a capacity of 33 000 tonnes/year, and uses about 95% recycled material (Table 8).

The size of a batch of copper produced is determined by the capacity of the converters. The converter is charged with copper matte (produced by smelting metal concentrates) as well as with metal scrap. The result, known as blister copper contains 97-98 % copper. The treating capacity of matte per batch in Kumera Peirce-Smith Converters can vary between 100-400 tonnes, depending on the smelter capacity and other requirements (information from www.kumera.com).

The main waste product is slag, which consists mainly of iron silicates and is used mainly for road construction. The amount of slag produced by the smelter was about 500 000 tonnes in 2007 (Boliden, 2007), containing about 2500 tonnes of copper. Dusts and sludges from flue-gas treatment are also important waste products. About 400 tonnes were produced in 2007; the actual copper content of this dust is not reported, but probably very low. The amount of slag and dust can be related to the total amount of material processed (primary and secondary) which was 1430 000 tonnes. Some of these go back into the process, while others are stored for eventual use in a further refining process or for being disposed of as hazardous waste.

3.3.3. Aluminium smelters

There is only one plant producing primary aluminium in Sweden, and this produces 134 000 tonnes per year.

The largest aluminium smelter for aluminium recycling uses 100 % recycled material, though this also includes waste material from the primary industry. 90 000 tonnes of incoming scrap is processed here per year (Table 8). The turnover time of material in the store for incoming material is usually 2-4 weeks, though the time can be longer for certain special types of material. The maximum amount of material in storage is 10 000 tonnes, but the facility aims to store not more than 5000 tonnes. The smelter receives aluminium direct from Studsvik, but limits the fraction of Studsvik's cleared aluminium in each smelt to 5 %, in accordance with Studsvik's conditional clearance.

A further plant based on recycled aluminium produces about 70 000 tonnes of aluminium per year, of which about 60 % comes from scrap. There are a number of smaller foundries but these use very little "post consumer" aluminium and are based mainly on re-smelting primary waste (process scrap) (personal communication, Svenskt Aluminium).

There are a large number of different grades of aluminium product, for example with regard to the silica content. Scrap aluminium is therefore sorted into different grades for use in producing different grades of product. The aluminium can also be prepared to some extent at the smelter, using

[5] Boliden (2007). Miljörapport, 2007. Rönnskärsverken och Rönnskärs hamn.
[6] Boliden (2015). Metals for modern life.
[7] Boliden (2012). Sustainability report, Rönnskär, 2012

clipping and pressing. Personnel are occupied full-time with this process. At the individual aluminium smelters, the size of a specific smelt, or "batch" of smelted material varies. Smelting ovens have capacities between 2 and 33 tonnes. Of the aluminium smelters using recycled material, the smaller facility has ovens between 8 and 33 tonnes in capacity.

The main waste products are slag and salt slag (generated by addition of sodium chloride and calcium chloride to the molten aluminium as protection against oxidation). About 20 000 tonnes of these are generated each year. The slag is processed to extract iron and aluminium and the remaining 18 000 tonnes is disposed of in Germany as hazardous waste. Fly ash and dust from the flue gas scrubber is also sent to be disposed of as hazardous waste.

The main uses of the aluminium produced are the production of vehicles, in telecommunications (base stations and other uses), household appliances, building industry and furniture. Work is currently being carried out to classify a treated form of slag as a product for various reuses. The slag is treated with lime and dolomite, the resulting slag is calcium aluminate. This material can be used as a synthetic flux for use in steelworks and can also be used in the production of cement.

3.4. Summary of material flows

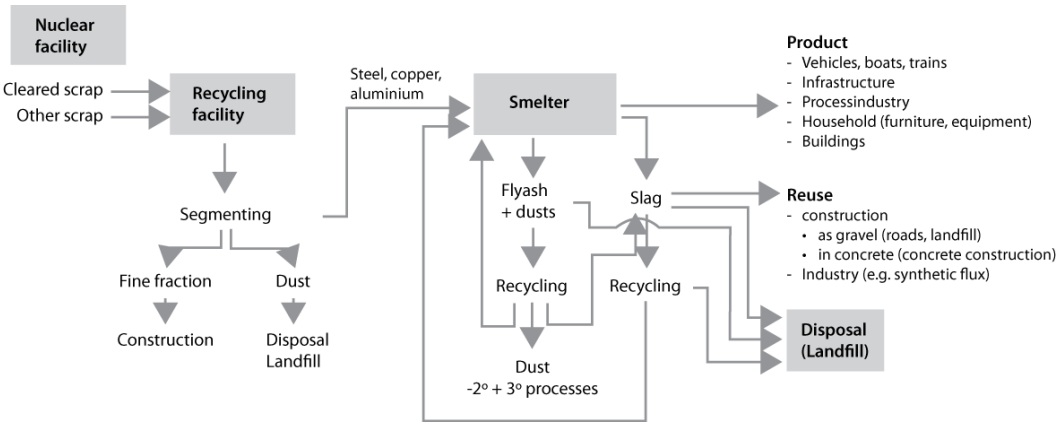

Figure 1 An overview of the processes, materials and products considered for the recycling of materials.

Table 8 Information from interviews with metal works/environmental reports

Steel work/mill	**Scrap used**	**Primary material used**	**Production**	**Fraction scrap in product**	**By-products**					
					slag			**Fly ash/dust**		
	tonnes/year	tonnes/year	tonnes/year		tonnes/year	per tonne product	destination (tons)	tonnes/year	per ton product	destination (tonnes)
Ore-based 1 steel	90 000	Ore: 2055000	1 659 000	0.05	160 000	0.10	Return to process (50 000) Landfill construction (80 000) Stored for eventual use (30 000)	35 000	0.0211	Return to process (26 000) Landfill (8 000)
Ore-based 2 steel	14 000	Ore: 1144400	990 000	0.01	90256	0.09	Return to process (85 000) Internal disposal site/stock-pile (56 000)	1820	0.0018	Landfill (1740) Used (81)
Carbon steel	360 000	0	360 000	1.00		0.10	Production of asfalt. Metal extraction from mill scale - (0.001)	430	0.0012	Extraction of zinc
Stainless steel	330 000	1/3 total amount	500 000	0.66	130 000 - 140 000	0.40	Extraction of metals (returned to production) and disposal in landfill	14150		Extraction of nickel, chromium, iron - returned to production. Zinc extraction from secondary dust.
Aluminium	90 000	0	90 000		18 000	0.20	Disposal as hazardous waste (today). Synthetic flux for use in steel production (under development). Additive to cement (under development).			Disposal as hazardous waste.
	70 000	28 000								
Copper	60 000 copper (total weight 160 000 tons)	165 000 copper in ore concentrates (total 600 000 tons)	214 000	0.30	2 500 tons copper, (total 500 000 tons)		Extraction of zinc oxide, followed by extration of zinc. Use in construction (e.g. in roads).	total weight 400 tons		
Brass	33 000	1.7								

4. Review of relevant scenarios and input data

As discussed in Section 1.1, the general clearance levels determined in IAEA (2005) have been adopted in BSS (2013), and the clearance levels recommended for scrap metals in RP89 were derived in RP117. The scenarios included in these studies are given in the introduction (Tables 1 and 2). Some radionuclides have short-lived daughters that are considered to be in secular equilibrium with the parent, and are therefore included in the exposure calculations. These radionuclides are written with a "+" after the mass number, e.g. $^{90+}$Sr.

In IAEA (2005), the scenarios that defined the clearance levels for the radionuclides considered in this study were: Resident (1-2 year old child) near landfill or other facility (seven radionuclides: ^{14}C, $^{109+}$Cd, ^{3}H, ^{59}Ni, ^{63}Ni, $^{90+}$Sr, ^{99}Tc,); Resident (adult) in house constructed of contaminated material (eighteen radionuclides: $^{108m+}$Ag, $^{110m+}$Ag, $^{144+}$Ce, ^{57}Co, ^{60}Co, ^{134}Cs, $^{137+}$Cs, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{40}K, ^{54}Mn, ^{22}Na, ^{94}Nb, $^{106+}$Ru, $^{125+}$Sb, $^{113+}$Sn, ^{65}Zn,); Resident (1-2 year old child) near public place constructed with contaminated material (^{55}Fe), and; Worker on landfill or in other facility (other than foundry) (ten radionuclides: ^{241}Am, ^{244}Cm, ^{60}Co, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{124}Sb, ^{46}Sc, $^{95+}$Zr). Note that the relevant U isotopes were only assessed separately as naturally-occurring radionuclides. The scenarios in IAEA (2005) are not directly related to metal recycling and so are not directly relevant to the current study.

Therefore, RP117 and its sister report RP89 are considered in detail below, and two relevant studies from the USA (US EPA 2001; NUREG 1640) are used to support the critical evaluation of the scenarios, parameters and assumptions applied.

4.1. Information associated with the assumptions in RP89/RP117

The clearance process is applied to materials that have been inside controlled areas of nuclear facilities. Therefore, only a proportion of the scrap metal that arises from the decommissioning of a reactor facility is potentially clearable, the other material is either too active or arises from outside the controlled areas. RP89 discussed the typical amounts of scrap metal that will arise during decommissioning of reactors. During normal operation, about 10-50 tonnes/year clearable metal is released from each reactor, while much larger masses are cleared during decommissioning. The interval for amounts cleared during normal operation was confirmed by the information from Swedish power stations. The estimated rates of metal clearance from decommissioning in the EU from RP89 are shown in Table 9. RP89 also states that "Roughly 8,000 to 13,000 tonnes of metal are used in the controlled area of a commercial reactor of which during dismantling roughly 50% to 70% is potentially clearable". Therefore, the amounts of metals assumed to be cleared per year in the EU in RP89 are consistent with the maximum amount of metal cleared during the decommissioning of one commercial reactor.

Table 9 Quantities of metal assumed to be cleared from EU facilities in RP89/RP117

Clearable material	Quantity tonnes/y
Steel and stainless steel	10 000
Copper and copper alloys	200

Aluminium and aluminium alloys*	1 500 (40)
Direct reuse (all metals)	1 000

*40 Mg/y is for power plants and 1,500 Mg/y for enrichment facilities

In the different scenarios in RP117, the cleared scrap metal is assumed to be mixed with other scrap in the scrap yard, since scrap yards collect material from a number of sources. The dilution continues along the material flowpath, every time there is an additional input of non-cleared material. However, for metal products, the level of dilution considered is often lower than the annual dilution at a given facility, since there is the possibility that cleared material comprises a greater proportion of the metal in a given melt, and this could be used to make a metal product. RP89/RP117 used the term "fraction of very low level waste (VLLW)" to describe the level of dilution assumed in each scenario.

For steel, RP89 assumed that 4000 tonnes of carbon steel were processed each year in a plant using electric arc furnaces (EAF) and 2000 tonnes of stainless steel in a plant using induction furnaces (IF). Foundries typically have smaller furnaces (around 0.5 to 7 tonnes for induction furnaces and 10 to 100 tonnes for electric arc furnaces) than steel mills (10 to 125 tonnes for electric arc furnaces and 100 to 300 tonnes for oxygen blast furnaces) (RP89). The sizes of the different types of furnaces in RP89 agree with the information collected in this study. From the information received in this study, arc furnaces are the most relevant type of furnace in Sweden today, but replacement with the more energy effective induction furnaces is a possibility in the future. RP89 applied a range of dilution factors of VLLW in the scenarios, and the steel and stainless steel products were assumed to comprise 10% or 20% cleared scrap, respectively. A more comprehensive list of the fractions of VLLW applied is given in Section 5.1 of this report (Table 15).

Recycling of low quality copper involves several processing stages, while high quality scrap can be treated in a single stage at a foundry. At nuclear power plants, potentially clearable copper comes primarily from electrical equipment in the form of cables (RP89). The insulation material was assumed to be removed prior to clearance of the copper in RP89/RP117. Since the copper in cables is of high quality, RP89 assumed that products could consist of up to 30% cleared copper, reflecting direct treatment at a foundry with a low level of dilution with other material. The dilution factor accounts for dilution with other scrap and other materials in the products (e.g. zinc in brass products).

Relatively small quantities of potentially clearable aluminium are present in power plants while much larger amounts are present in fuel enrichment plants (see Table 9). Separate calculations were therefore carried out in RP117 specifically for uranium isotopes in scrap from a fuel enrichment plant. According to RP89, three different types of furnace can be used to recycle aluminium, and their capacity ranges from 0.5 – 20 tonnes. In Sweden, the largest furnaces have a capacity of up to 33 tons. In RP117, the products were assumed to contain 20% cleared scrap.

During smelting, radionuclides redistribute into the metal, slag and/or dust, according to their chemistry. Therefore, distribution factors were included in the assessment for each radionuclide during the smelting of each metal. Furthermore, since the slag and dust provide a smaller mass of matrix, radionuclides that move into these fractions undergo a physical concentration process. Therefore, smelting method-dependent concentration factors were applied to account for this physical process in the dust and slag.

Radioactive decay was only accounted for in the residential scenarios, where it can be assumed that a certain time has passed before houses can be built on a landfill. Therefore, for some shorter-lived radionuclides in some of the scenarios, the clearance levels may be quite conservative. An example is the Boat scenario, where the time to the build the boat would be significant.

4.2. Limiting scenarios in RP117

The clearance levels in RP89 are defined by the maximum annual dose calculated in the RP117 scenarios. The RP117 scenarios that delivered the highest dose rates for the radionuclides considered in this study (Table 5) in the steel, copper and aluminium scenarios are given in Table 10. Note that skin dose scenarios are evaluated against a dose of 50 mSv/a instead of 10 µSv/a.

Table 10 Limiting scenarios in RP117. The most limiting scenario from the three metals is given in bold. Note: AF = Arc Furnace; IF = Induction Furnace; L = Landfill; W = Worker; EXT = External; ING = Ingestion; INH = Inhalation; AG3 = from a fuel fabrication plant

Nuclide	**Most restrictive clearance level**	**Limiting scenario for each metal**		
		Steel recycling	Copper recycling scenario	Aluminium recycling scenario
Ag-108m+	Steel	**Boat AF (EXT)**	Musical instrument (EXT effective)	Transport scrap (EXT)
Ag-110m+	Steel	**Boat AF (EXT)**	Musical instrument (EXT effective)	Transport scrap (EXT)
Am-241	Steel	**Player IF (INH)**	Manufacture of ingots (INH)	Slag processing (INH)
C-14	Steel	**Steel plant IF (ING)**	Refining (INH)	Refining (INH)
Cd-109+	Steel	**Steel plant IF (ING)**	Refining (INH)	Fishing boat (EXT)
Ce-144+	Steel	**Slag L. IF W (EXT)**	Musical instrument (SKIN)	Slag processing (EXT)
Cm-244	Steel	**Player IF (INH)**	Manufacture of ingots (INH)	Slag processing (INH)
Co-57	Steel	**Boat AF (EXT)**	Slag disposal – waste handling (EXT)	Fishing Boat (EXT)
Co-58	Steel	**Boat AF (EXT)**	Transport scrap (EXT)	Transport scrap (EXT)
Co-60	Steel	**Boat AF (EXT)**	Transport scrap (EXT)	Transport scrap (EXT)
Cs-134	Steel	**Dust L. AF W (EXT)**	Transport scrap (EXT)	Slag processing (EXT)
Cs-137+	Steel	**Dust L. AF W (EXT)**	Transport scrap (EXT)	Slag processing (EXT)
Eu-152	Steel	**Slag L. IF W (EXT)**	Musical instrument (EXT effective)	Slag processing (EXT)
Eu-154	Steel	**Slag L. IF W (EXT)**	Musical instrument (EXT effective)	Slag processing (EXT)
Eu-155	Aluminium	Slag L. IF W (EXT)	Musical instrument (EXT effective)	**Slag processing (EXT)**
Fe-55	Steel	**Steel plant IF (ING)**	Refining (INH)	Refining (INH)
H-3	Steel	**Steel plant (Atmos)**	Refining (INH)	Refining (INH)
K-40	Steel	**Dust L. AF W (EXT)**	Transport scrap (EXT)	Transport scrap (EXT)
Mn-54	Steel	**Boat AF (EXT)**	Transport scrap (EXT)	Transport scrap (EXT)
Na-22	Steel	**Dust L. AF W (EXT)**	Transport scrap (EXT)	Slag processing (EXT)
Nb-94	Steel	**Slag L. IF W (EXT)**	Musical instrument (EXT effective)	Slag processing (EXT)
Ni-59	Copper	Boat AF (EXT)	**Musical instrument (SKIN)**	Refining (INH)
Ni-63	Copper	Steel plant IF (ING)	**Refining (INH)**	Refining (INH)
Pu-238	Steel	**Player IF (INH)**	Manufacture of ingots (INH)	Slag processing (INH)
Pu-239	Steel	**Player IF (INH)**	Manufacture of ingots (INH)	Slag processing (INH)
Pu-240	Steel	**Player IF (INH)**	Manufacture of ingots (INH)	Slag processing (INH)
Pu-241	Steel	**Player IF (INH)**	Manufacture of ingots (INH)	Slag processing (INH)
Ru-106+	Steel	**Dust L. AF W (EXT)**	Transport scrap (EXT)	Refining (INH)
Sb-124	Aluminium	Boat AF (EXT)	Musical instrument (EXT effective)	**Slag processing (EXT)**
Sb125+	Steel	**Boat AF (EXT)**	Musical instrument (EXT effective)	Slag processing (EXT)
Sc-46	Steel	**Slag L. IF W (EXT)**	Musical instrument (EXT effective)	Slag processing (EXT)
Sn-113+	Steel	**Dust L. AF W (EXT)**	Transport scrap (EXT)	Slag processing (EXT)
Sr-90+	Copper	Steel plant IF (ING)	**Musical instrument (EXT effective)**	Fishing boat (EXT)
Tc-99	Steel	**Slag L. IF Child**	Landfill child	Landfill Child
U-234	Aluminium	Player IF (INH)	Manufacture of ingots (INH)	**Slag processing (INH) (AG3)**
U-235+	Aluminium	Player IF (INH)	Manufacture of ingots (INH)	**Slag processing (EXT) (AG3)**
U-238+	Aluminium	Player IF (INH)	Manufacture of ingots (INH)	**Slag processing (INH) (AG3**)
Zn-65	Steel	**Dust L. AF W (EXT)**	Transport scrap (EXT)	Transport scrap (EXT)
Zr-95+	Aluminium	Boat AF (EXT)	Musical instrument (EXT effective)	**Slag processing (EXT)**

Steel recycling scenarios most commonly defined the clearance level, and the relevant limiting RP117 scenarios are:

- Steel recycling: Boat AF (EXT), Steel plant IF (ING), Dust L. AF W (EXT), Slag L. IF W (EXT),), Player IF (INH), Slag L. IF Child, Steel plant (Atmos)
- Copper recycling: Musical instrument (EXT effective), Musical instrument (SKIN), Refining (INH)
- Aluminium recycling: Slag processing (INH) (AG3), Slag processing (EXT) (AG3), Slag processing (EXT)

4.2.1. Steel recycling scenarios

The Boat AF (EXT) scenario (Appendix A Section 3.5.1.4 of RP117) defined the clearance level for Ag isotopes, Co isotopes, ^{54}Mn and $^{125+}$Sb, and was the most restrictive steel recycling scenario for ^{59}Ni, ^{124}Sb and $^{95+}$Zr. It involves external exposure to gamma emitters that remain in steel during smelting from the occupational use of a boat made from recycled steel from an arc furnace. Reasons for its importance include the 5000 hours/year that a professional sailor spends aboard a boat, which is ~3 times longer than a normal working year, and the geometry and proximity of the carbon steel in the vessel. Radioactive decay is not accounted for in the time taken to recycle the cleared metal, build and fit the boat, and this would have significantly reduced the doses from many of the nuclides, including those for which the scenario is most restrictive; (^{108m}Ag, ^{110m}Ag, ^{57}Co, ^{58}Co, ^{54}Mn, ^{124}Sb and ^{95}Zr have half-lives less than one year). The text in RP117 suggests that the exposure time should only reflect the time spent near the hull, but the doses are calculated on the basis of the sailor being 1 m from the hull over the full exposure time. This means that the doses reported have a tendency to be conservative.

The Steel plant IF (ING) scenario (Appendix A Section 3.2.2.2 in RP117) defined the clearance level for ^{14}C, $^{109+}$Cd, and ^{55}Fe, and was the most restrictive steel recycling scenario for ^{63}Ni and $^{90+}$Sr. It involves the exposure of a worker at an induction furnace steel plant via ingestion of 0.15 g of dust/day over 225 days/year. Distribution factors were applied to account for the amount of each radionuclide that is associated with the dust, and the physical concentration factor for the dust in an induction furnace was applied. Although the worker would also be exposed via inhalation of dust, the inclusion of both pathways would not have affected the clearance levels derived for ^{14}C, $^{109+}$Cd or ^{55}Fe in RP117 due to the values involved (the ingestion dose was dominating) and the rounding procedure applied.

The Dust L. AF W (EXT) scenario (Appendix A Section 3.6.1.1 in RP117) defined the clearance levels for ^{134}Cs, $^{137+}$Cs, ^{40}K, ^{22}Na, $^{106+}$Ru and ^{65}Zn, and estimates the external dose received by a landfill worker who disposes the dust from an Arc furnace throughout the working year (1800 hours/year). The Slag L. IF W (EXT) scenario (also in Appendix A Section 3.6.1.1 in RP117) defined the clearance level for $^{144+}$Ce, ^{152}Eu, ^{154}Eu, ^{94}Nb and ^{46}Sc and was the most restrictive steel recycling scenario for ^{155}Eu. This scenario estimates the external dose received by a landfill worker who disposes the induction furnace slag throughout the working year. The scenarios assume that the dust and slag from the steel works comprises a given fraction of the total material disposed of in the landfill each year.

The Player IF (INH) (Appendix A Section 3.6.2.1.1 in RP117) scenario defined the overall clearance level for several actinides (Pu isotopes, ^{241}Am and ^{244}Cm) and was the most restrictive steel recycling scenario for U isotopes. It involves the internal exposure of football players via inhalation following the use of induction furnace slag to build a football field. This scenario led to doses that were significantly higher than the inhalation doses calculated for slag disposal workers (Slag L. IF W (INH)) even though the exposure times were shorter (264 vs 1800 hours/year) because:

- The slag in the playing field was not assumed to be mixed with other materials, while the landfill was assumed to accept materials from other sources

- The workers at the landfill were considered to spend the majority of their time in the vehicle, where the dust concentration (2×10^{-4} g/m^3) was an order of magnitude lower than estimated for the playing field during high levels of activity (half the exposure time for the player)
- To some extent, the higher breathing rates applied (1.8 (high level of activity) and 1.5 (intermediate level of activity) vs 1.2 m^3/h)

The Player scenario is not considered to be realistic in Sweden, as slag is not used to make this type of playing field. If the Player and the related Spectator scenarios are not included, the Scrap cutting scenario delivers the highest doses for Pu isotopes, ^{241}Am and ^{244}Cm.

RP117's scrap cutting scenario (Appendix A Section 3.1.2 in RP117) assesses the evolution of the dust concentration in the room where the scrap is cut, and the calculations of the activity concentration in the dust are based on experimental data obtained for uranium for cutting artificially contaminated steel with an oxyacetylene torch. This prevented the extrapolation of the data to radionuclides other than actinides. The calculations are also based on a surface contamination of 1 Bq/cm^2, rather than the 1 Bq/g used in the other dose assessments. A different approach was used in NUREG 1640 and US EPA (2001): the radionuclide concentration of the dust was assumed to be the same as in the metal, thus all radionuclides were included in the scenario; dust concentrations were based on data from relevant workplaces, as was the time spent on the activity.

In Sweden, a variety of cutting techniques are used (Section 3.2); including shearing the metal, and using shredders and hammer mills. Shearing takes place outside and is used to minimise dust formation, while specific measures are used to control the dust created by shredders and hammer mills. Therefore, the RP117 Scrap cutting scenario does not obviously describe the situation in Swedish scrap yards and the doses from the inhalation of dust during shredding need to be calculated in a different way. The adaptation of this scenario is described in Section 5.4 and is based on the approach in NUREG 1640 and US EPA (2001).

The Slag L. IF Child (Appendix A Section 3.6.1.4 in RP117) describes a child living on a closed landfill. This scenario includes a radioactive decay period of 10 years, the period after which a slag landfill can be reused. The scenario includes external exposure, dust inhalation, ingestion of vegetables grown in the garden and inadvertent ingestion of soil.

In the Steel plant (Atmos) scenario (Appendix A Section 3.3.4.2 in RP117) was most restrictive for ^{3}H. The ^{3}H emission rate at the stack is based on the dilution of the scrap and the annual capacity of the steel plant, since all ^{3}H is considered to be vaporised, even though not all ^{3}H is considered to be released. A 400 000 tonne/year Arc furnace is considered in the scenario. This scenario is slightly different for other radionuclides as they associate with dust rather than volatilise.

4.2.2. Copper refining scenarios

The copper Refining (INH) scenario (Appendix B Section 3.3.1 in RP117) defined the clearance level for ^{63}Ni. This assumed that the dust concentration was 60% of the maximum allowable respirable dust concentrations in the workplace (3×10^{-3} g/m^3) throughout the working year and accounted for radionuclide distribution into the dust fraction and the effect of the reduced mass of the matrix on the radionuclide concentrations. Standard breathing rates were applied (1.2 m^3/h).

The copper Musical instrument (SKIN) scenario (Appendix B Section 3.9.1d in RP117) defined the clearance level for ^{59}Ni while the Musical instrument (EXT effective) scenario (also Appendix B Section 3.9.1d in RP117) defined the clearance level for $^{90+}$Sr and was the most restrictive copper recycling scenario for $^{108m+}$Ag, $^{110m+}$Ag, ^{152}Eu, ^{154}Eu, ^{94}Nb and $^{125+}$Sb. These scenarios involve

a professional French horn player playing their instrument for 1622 hours/year, and the instrument containing 30% cleared copper.

4.2.3. Aluminium recycling scenarios

The aluminium Slag processing (EXT) (PWR) scenario (Appendix B Section 3.4.3 in RP117) defined the clearance level for ^{155}Eu, ^{124}Sb and $^{95+}$Zr, while the Slag processing (INH) (AG3) scenario defined the clearance level for ^{234}U and $^{238+}$U and the Slag processing (EXT) (AG3) scenario defined the clearance level for $^{235+}$U (all scenarios described in (Appendix B Section 3.4.3 in RP117). These scenarios consider the external and inhalation doses to workers involved in aluminium slag processing, where the cleared scrap comes from either a pressurised water reactor (PWR) or a uranium enrichment plant (AG3). The effect of the mass of slag on the radionuclide concentrations is accounted for, the dust concentration is assumed to be 1 x 10^3 g/m^3, Standard breathing rates were applied (1.2 m^3/h).

4.3. Comparison with limiting scenarios in NUREG 1640

The scenarios applied in the determination of the doses received following the clearance of scrap from nuclear installations in the USA (NUREG 1640) are given in Appendix B.

4.3.1. Steel recycling scenarios

The most limiting steel recycling scenarios for each of the relevant radionuclides in these studies are shown in Table 5, together with the limiting steel scenario in RP117. The doses calculated for the clearance of metal with 1Bq/g contamination of a given radionuclide in NUREG 1640 are compared with those in RP117. It should be noted that the actual clearance levels are concentrations based on these doses and the dose criterion of 10 µSv/year, and a rounding procedure is applied, as described in Section 1.1.

Table 11 Most restrictive steel recycling scenario in RP117 and NUREG 1640 together with a comment on the exposure material (scrap, steel, dust or slag) and the route of exposure (external, inhalation, ingestion). Note: AF = Arc Furnace; IF = Induction Furnace; L = Landfill; W = Worker; EXT = External; ING = Ingestion; INH = Inhalation

Nuclide	RP117	NUREG 1640	Dose pathways considered RP117	Dose pathways considered NUREG 1640	Ratio of the doses calculated per Bq/g in the most restrictive steel scenarios (RP117/NUREG 1640)
Ag-108m+	Boat AF (EXT)	Scrap yard	Steel; external	Scrap; external, inhalation, ingestion	0.42
Ag-110m+	Boat AF (EXT)	Scrap yard	Steel; external	Scrap; external, inhalation, ingestion	0.38
Am-241	Player IF (INH)	Processing steel slag	Slag; inhalation	Slag; external, inhalation, ingestion	2.9
C-14	Steel plant IF (ING)	Leachate-industrial scrap	Dust; ingestion	Scrap; ingestion	4.0
Cd-109+	Steel plant IF (ING)	Scrap disposal-industrial	Dust; ingestion	Scrap; external	8.2
Ce-144+	Slag L. IF W (EXT)	Scrap yard	Slag, external	Scrap; external, inhalation, ingestion	0.82
Cm-244	Player IF (INH)	Handling slag	Slag; inhalation	Slag; external, inhalation, ingestion	2.9
Co-57	Boat AF (EXT)	Scrap disposal-industrial	Steel; external	Scrap; external	0.59
Co-58	Boat AF (EXT)	Scrap yard	Steel; external	Scrap; external, inhalation, ingestion	0.42
Co-60	Boat AF (EXT)	Scrap yard	Steel; external	Scrap; external, inhalation, ingestion	0.33
Cs-134	Dust L. AF W (EXT)	EAF dust-dump trailer	Dust, external	Dust; external, inhalation, ingestion	1.2
Cs-137+	Dust L. AF W (EXT)	EAF dust-dump trailer	Dust, external	Dust; external, inhalation, ingestion	1.2
Eu-152	Slag L. IF W (EXT)	Scrap yard	Slag, external	Scrap; external, inhalation, ingestion	0.99
Eu-154	Slag L. IF W (EXT)	Scrap yard	Slag, external	Scrap; external, inhalation, ingestion	0.91
Eu-155	Slag L. IF W (EXT)	Scrap disposal-industrial	Slag, external	Scrap; external	0.36
Fe-55	Steel plant IF (ING)	Scrap yard	Dust; ingestion	Scrap; external, inhalation, ingestion	0.50
H-3	Steel plant (Atmos)	Leachate-industrial scrap	Dust; inhalation and ingestion	Scrap; ingestion	0.37
K-40	Dust L. AF W (EXT)	Scrap yard	Dust, external	Scrap; external, inhalation, ingestion	1.65
Mn-54	Boat AF (EXT)	Scrap yard	Steel; external	Slag; external, inhalation, ingestion	0.38
Na-22	Dust L. AF W (EXT)	Scrap yard	Dust, external	Scrap; external, inhalation, ingestion	1.64
Nb-94	Slag L. IF W (EXT)	Scrap yard	Slag, external	Scrap; external, inhalation, ingestion	0.83

Nuclide	RP117	NUREG 1640	Dose pathways considered RP117	Dose pathways considered NUREG 1640	Ratio of the doses calculated per Bq/g in the most restrictive steel scenarios (RP117/NUREG 1640)
Ni-59	Boat AF (EXT)	Scrap yard	Steel; external	Dust; external, inhalation, ingestion	0.06
Ni-63	Steel plant IF (ING)	Scrap yard	Dust; ingestion	Dust; external, inhalation, ingestion	0.09
Pu-238	Player IF (INH)	Scrap yard	Slag; inhalation	Scrap; external, inhalation, ingestion	3.4
Pu-239	Player IF (INH)	Scrap yard	Slag; inhalation	Scrap; external, inhalation, ingestion	3.4
Pu-240	Player IF (INH)	Scrap yard	Slag; inhalation	Scrap; external, inhalation, ingestion	3.4
Pu-241	Player IF (INH)	Scrap yard	Slag; inhalation	Scrap; external, inhalation, ingestion	3.5
Ru-106+	Dust L. AF W (EXT)	Scrap yard	Dust, external	Scrap; external, inhalation, ingestion	1.7
Sb-124	Boat AF (EXT)	Scrap yard	Steel; external	Scrap; external, inhalation, ingestion	0.39
Sb-125+	Boat AF (EXT)	Scrap yard	Steel; external	Scrap; external, inhalation, ingestion	0.44
Sc-46	Slag L. IF W (EXT)	Scrap yard	Slag, external	Scrap; external, inhalation, ingestion	0.9
Sn-113+	Dust L. AF W (EXT)	Scrap yard	Dust, external	Scrap; external, inhalation, ingestion	1.7
Sr-90+	Steel plant IF (ING)	Leachate-steel slag	Dust; ingestion	Slag; ingestion	1.7
Tc-99	Slag L. IF Child	Leachate-industrial scrap	Slag; External, ingestion and inhalation	Scrap; ingestion	0.08
U-234	Player IF (INH)	Leachate-industrial scrap	Slag; inhalation	Scrap; ingestion	0.75
U-235+	Player IF (INH)	Leachate-industrial scrap	Slag; inhalation	Scrap; ingestion	0.56
U-238+	Player IF (INH)	Leachate-industrial scrap	Slag; inhalation	Scrap; ingestion	0.69
Zn-65	Dust L. AF W (EXT)	EAF dust-dump trailer	Dust, external	Dust; external, inhalation, ingestion	1.3
Zr-95+	Boat AF (EXT)	Scrap yard	Steel; external	Steel; external	0.74

External exposure is the most important exposure pathway for medium to high energy gamma emitters. The external exposure steel recycling scenarios that controlled clearance levels in RP117 were Boat (EXT; $^{108m+}$Ag, $^{110m+}$Ag, ^{57}Co, ^{58}Co, ^{60}Co, ^{54}Mn, ^{59}Ni, ^{124}Sb, $^{125+}$Sb, $^{95+}$Zr), Dust L. AF W (EXT, ^{134}Cs, $^{137+}$Cs, ^{40}K, ^{22}Na $^{106+}$Ru, $^{113+}$Sn, ^{65}Zn) and Slag L. IF W (EXT; ^{144}Ce, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{94}Nb, ^{46}Sc). Most of the radionuclides that gave their highest doses in these scenarios gave their highest doses in the Scrap yard scenario in NUREG 1640, which included external exposure. NUREG 1640's Scrap yard scenario was identified as important for three reasons: there is limited time for radioactive decay before handling, all radionuclides are still present in the material and scrap yard workers spend much of their workday in close proximity to large quantities of scrap. The NUREG 1640 Scrap yard scenario generated doses from 1 Bq/g contamination that were slightly higher than the doses calculated in the RP117 Boat (EXT) scenario, similar to those in the RP117 Slag L. IF W (EXT) scenario and slightly lower than those in the Dust L. AF W scenario, for the relevant radionuclides. The differences between the doses were mostly negligible, given that the clearance levels are based on rounding up or down to within a factor of 3 (Section 1.1). Five of the radionuclides that led to the highest doses in the Dust L. AF W (EXT) scenario in RP117 led to the highest doses in the EAF dust-dump trailer scenario in NUREG 1640; ^{40}K, ^{22}Na, $^{106+}$Ru, $^{113+}$Sn and ^{65}Zn. These scenarios are both related to dust handling but Dust L. AF W (EXT) describes disposal of dust at a landfill while EAF dust-dump trailer describes the transport of the dust. These scenarios led to reasonably similar normalised doses, although the doses in RP117 were higher.

The NUREG 1640 Scrap yard scenario was also most restrictive for some nuclides that are most hazardous on ingestion (^{55}Fe, ^{63}Ni) or inhalation (^{238}Pu, ^{239}Pu and ^{240}Pu), because it includes inhalation and ingestion of the dust generated while cutting scrap (up to 0.02 g/h). The scrap yard cutting scenario in RP117 is limited to inhalation of selected actinides, however, for the actinides (Pu isotopes, ^{241}Am, ^{244}Cm and $^{238+}$U) it is an important scenario that delivers doses within a factor 3 of the limiting scenario. The Pu-isotope doses calculated for inhalation during cutting were therefore comparable between the two studies, suggesting the pathway is adequately represented in RP117 for the isotopes included. However, Table 11 suggests that the exclusion of ^{55}Fe and ^{63}Ni from this scenario in RP117 may lead to an underestimation of the maximum exposure from steel. It should be noted that the clearance level for nickel isotopes was restricted by copper scenarios (see below).

Since the actinides concentrate in slag during smelting, the scenario that led to the greatest exposure for all actinides in steel scenarios in RP117 involved a sports person inhaling dust while playing regularly on an artificial playing surface constructed of slag. The US EPA (2001) and NUREG 1640 did not have an equivalent scenario, thus other scenarios involving internal exposure were most restrictive for these radionuclides.

NUREG 1640 included leachate scenarios for the disposal of the cleared scrap metal, dust and slag, which were not considered in RP117. The Scrap leachate scenario led to the greatest exposures from steel recycling for some relatively mobile radionuclides, ^{3}H, ^{14}C, ^{99}Tc, and U-isotopes, while the slag leachate scenario led to the highest normalised doses from $^{90+}$Sr. In RP117, ingestion of dust at an induction furnace (Steel plant IF (ING)) was the most restrictive for ^{14}C and $^{90+}$Sr, as well as ^{55}Fe and ^{63}Ni, while atmospheric releases of ^{3}H (Steel plant (ATMOS)), exposure from ^{99}Tc due to residential housing built on a landfill that received slag (Resident Child) and the Player scenario (U isotopes) were most restrictive. Although the main exposure pathways identified in RP117 are quite different, most of the normalised doses calculated were within a factor of three of the doses calculated in the leachate scenarios. The exception to this is ^{99}Tc where the RP117 dose for a child exposed to slag leachate was more than an order of magnitude lower than the normalised dose from the limiting NUREG 1640 Scrap leachate scenario. Cleared scrap can be sent for landfill in Sweden, but this only occurs when it is classified as a hazardous material on the grounds of chemical contaminants. Therefore, the assumption in NUREG 1640 that 0.8 of the

waste in a landfill volume is cleared scrap is in vast excess of the situation in Sweden. Furthermore, the maximum infiltration rate applied at the landfill is 0.0526 m/year, while a hazardous waste facility in Sweden must limit the infiltration to 0.005 m/year (Förordning (2001:512) om deponering av avfall, based on the Landfill Directive (1999/31/EC)). Therefore, relevant parameters for this scenario in Sweden would reduce the doses received very significantly.

Overall, there is reasonably good agreement between the most restrictive steel recycling scenarios for the different radionuclides and the annual doses obtained in the two studies. This suggests that the sets of steel recycling scenarios applied include the main exposure pathways. The adequacy of the input data used in the different scenarios will be considered with a specific focus on Sweden in Chapter 5.

4.3.2. Copper and aluminium recycling scenarios

Some of the clearance levels defined in RP117 were calculated in scenarios involving copper or aluminium recycling. In NUREG 1640, however, steel scenarios were the most restrictive for all radionuclides. Table 10 shows the copper and aluminium recycling scenarios that defined RP117 clearance levels for certain isotopes, and the equivalent most restrictive scenarios for the relevant metal in NUREG 1640. The most restrictive scenario for ^{59}Ni in RP117 involved skin exposure of a professional musician to the copper produced, which is compared to an exposure limit of 50 mSv/a rather than the 10 µSv/a used for effective doses. For $^{90+}$Sr, it involved external exposure of the professional musician to the copper produced. This type of scenario was not included in NUREG 1640, where the scenario leading to the greatest exposure from copper recycling for ^{59}Ni and $^{90+}$Sr (Slag worker) generated normalised dose rates that were one – two orders of magnitude lower. RP117 applied a very conservative distribution for Sr during melting copper, with 100% in both the metal and the slag. NUREG 1640 assumed that 99% of the Sr was in the slag during fire refining, with a maximum of 15% in the metal (see further Section 5.2).

The clearance levels for U-isotopes are defined by the slag processing scenario, where the aluminium arises from a fuel fabrication plant (AG3). In this, it was assumed that 10% of the slag came from cleared aluminium. The normalised dose rates are >800 times those for the most restrictive aluminium scenario in NUREG 1640 (Scrap yard). External exposure and inhalation are considered in the RP117 scenario, while all exposure pathways are considered in the NUREG 1640 Scrapyard scenario. A major reason for the discrepancy in the magnitude of the doses calculated is the low level of dilution in the RP117 scenario, which considers a fuel fabrication plant containing ~20 times more aluminium than the power plant considered in NUREG 1640 and relatively low capacity furnaces (0.5 – 20 tonnes in RP117 vs 40 – 100 tonnes in NUREG 1640). In NUREG 1640, the smallest scrap yard considered is capable of processing 840 tonnes of aluminium per year and each reactor decommissioned is considered to contain only 2 tonnes of potentially clearable aluminium, thus there is also more dilution throughout the different scenarios.

The aluminium Slag processing (EXT) scenario also defined the clearance levels for ^{155}Eu, ^{124}Sb and $^{95+}$Zr, and this scenario gave dose rates that were well in excess of the maximum doses calculated in for aluminium scenarios in NUREG 1640, in the Scrap yard scenario.

Table 12 Comparison of the most restrictive scenarios in RP117 and NUREG 1640 for nuclides whose clearance levels were defined by copper or aluminium recycling scenarios in RP117. Note: EXT = External; INH = Inhalation; AG3 = from a fuel fabrication plant; SKIN = Skin dose

Nuclide	Metal that defined the clearance level in RP117	Clearance level-defining scenario in RP117	Most restrictive scenario in NUREG 1640 for the relevant metal	Comment on the distributions during melting applied	Ratio of the doses calculated per Bq/g in the most restrictive scenarios for copper or aluminium (RP117/NUREG 1640)
Eu-155	Aluminium	Slag processing (EXT)	Scrap yard	Similar	970
Ni-59	Copper	Musical instrument (SKIN)	Handling slag	Similar	27 (corrected for different dose limits)
Ni-63	Copper	Refining (INH)	Handling slag	Similar	20
Sb-124	Aluminium	Slag processing (EXT)	Scrap yard		1100
Sr-90+	Copper	Musical instrument (EXT effective)	Handling slag	Conservative distribution applied in RP117	120
U-234	Aluminium	Slag processing (INH) (AG3)	Scrap yard		870
U-235+	Aluminium	Slag processing (EXT) (AG3)	Scrap yard		1500
U-238+	Aluminium	Slag processing (INH) (AG3)	Scrap yard		810
Zr-95+	Aluminium	Slag processing (EXT)	Scrap yard		1600

5. Suitability of the exposure assumptions applied in RP117 for Sweden

5.1. Material flow

The suitability of the material flow assumptions applied in RP117 for Sweden will be assessed here through comparison with the information obtained in this study. However, since none of the Swedish nuclear facilities had estimated the total amount of steel, copper or aluminium that would be potentially clearable during decommissioning, these assumptions are based on the material quantity data in RP89, which are also representative of the amount of potentially clearable scrap from a reactor. In Sweden, decommissioning is estimated to take between 5 and 7 years, therefore the maximum amount of metal decommissioned in a given year is estimated to be one third of the total amount of clearable metal (Table 13). Additionally, no limit is placed on the proportion of the cleared material from a site that could reach a given facility, beyond the physical amount received. In RP89, only a part of the carbon steel was considered in the scenarios. The direct reuse category was considered to be zero in this study, since all information gathered suggests that direct reuse is highly unlikely in Sweden. Although no information was requested from the Swedish fuel fabrication plant, the data from RP89 for this type of facility has been included.

Table 13 Maximum mass of each metal considered to be cleared in a given year during decommissioning of a nuclear facility in Sweden

Clearable material	Quantity tonnes/y
Total steel and stainless steel cleared	3 300
- carbon steel cleared	2 600
- stainless steel cleared	700
Copper and copper alloys	70
Aluminium and aluminium alloys*	500 (15)
Direct reuse (all metals)	0

* 500 is from a fuel fabrication plant (based on RP89) and 15 from a reactor

The level of dilution of cleared scrap with other scrap at each stage of the material flow sequence in Sweden is summarised in Table 14, based on the information presented in Sections 3.1 – 3.4 and the clearable material in Table 13. The annual amount of each type of scrap cleared from the nuclear facility was divided by the material handled at each scrap yard per year, or by the mass of metal produced per year at each metal works. For the smaller metal works, the maximum mass of cleared scrap was taken into account when calculating the dilution factor, based on a 1:4 dilution at the scrap yard. Although the interviews highlighted that cleared material can be mixed with scrap metal from non-regulated activities at the internal recycling centres of the nuclear facilities, this is not included as it has only been quantified for one site, prior to the onset of decommissioning. The individual batches arriving at the recycling centres are expected to be mixed with scrap from other sources, as it was noted that items from a batch rarely remain together. Large items are either cut up at the nuclear facilities prior to clearance or at the recycling centres before onward transport to the steelworks thus these are also expected to undergo mixing with other scrap. Therefore the minimum level of dilution at the recycling centre is considered to be 0.2, reflecting all of the cleared scrap being received by the smallest recycling centre (Table 14).

Table 14 Scrap processed or metal produced per year at relevant facilities and the dilution of cleared scrap (Table 13) with other material processed at each site. The values selected for the calculations are shown in bold.

Recycling centre	Scrap processed per year (tonnes)	Dilution factor	
Company 1	130 000	0.03	
	20 000	**0.2**	
Company 2	48 000	0.07	
Metal works	**Metal produced per year**	**Dilution factor**	**Metal for which the dilution is calculated**
Ore-based steelworks	1 659 000	0.002	Carbon and stainless steel
	990 000	0.003	Carbon and stainless steel
Scrap based steelworks	360 000	**0.007**	Carbon steel
	500 000	**0.001**	Stainless steel
	6 461	0.192	Carbon steel
	213 555	0.006*	Carbon steel
	12 300	0.115	Carbon steel
	2 500	0.160	Carbon steel
Aluminium works 1	90 000	0.006 (0.0002)§	Aluminium
Aluminium works 2	70 000	**0.007 (0.0002) §**	Aluminium
Copper smelter	214 000	0.0003	Copper
Brass smelter	33 000	**0.002**	Copper

*Only 53% of the scrap metal comes from external sources

§ Values in brackets are for a nuclear reactor, the first value is from a fuel fabrication plant

Steel scrap is generally sent to large steel works, resulting in a high level of dilution with other materials. It is unlikely that all the cleared material will go to the smallest scrap yard and then this scrap yard provide all the scrap material needed at the smallest steelworks. If a small steelworks was to receive all of their scrap feed from the smallest recycling centre, it would lead to a much lower level of dilution that largely reflects dilution of the cleared material at the recycling centre, but this scenario is unlikely. The most representative dilution factors for Sweden in this study are those for the larger steelworks. Dilution factors of 0.007 and 0.001 are selected to describe dilution at carbon steel and stainless steel works, respectively. The exposure scenarios in RP117 are consistent with this assumption as they reflect large facilities (400 000 tonnes per year carbon steel; 200 000 tonnes/year stainless steel)

The interviews in this study suggest that, after clearance, scrap copper and aluminium are taken to a major recycling centre in Sweden and then onto large scale metal works. The maximum mass of these metals estimated to be cleared from a nuclear facility each year is a small fraction of the metal handled at the recycling and processing facilities. Since cleared material will arrive at the scrap yard in 15 tonne containers, dilution is expected to occur immediately as the scrap is sorted for onwards transport. Scrap copper is selected for a given melt on the basis of the quality of the copper to be produced, which could suggest that cleared copper cables remain in a batch. However, the small amounts of copper cleared each year, large amounts of copper processed each year and the large size of copper smelters, suggest that the cleared copper will be diluted to a significant extent. Therefore, it is assumed here that copper products contain at most 1% cleared copper. The RP117 scenarios involving very little dilution of the cleared copper prior to melting of the material and production of specific object are difficult to envisage in Sweden. Aluminium scrap is expected to be mixed with the other aluminium scrap during the sorting process at the recycling centre, and then at the aluminium smelter. Therefore the level of dilution in the products is expected to be high.

Table 15 compares the material flow assumptions in RP117 with the situation in Sweden, and the adjustments needed to the doses from the RP117 scenarios in order for the doses to be relevant for Sweden. For steel, many of the adjustments involve an increased exposure to the material. For example, a truck driver could spend five times longer transporting the scrap, based on a given person transporting all the scrap to scrap yard (2 hour journey; 15 tonne load; 3400 tonnes/year), and cleared scrap could comprise a larger part of the total scrap handled at the scrap yard, assuming that the smallest scrap yard received all the material cleared. Since it is possible that, after dilution in the scrap yard, the cleared scrap is melted in a batch and then turned into a product, the level of dilution in the products would reflect dilution at the scrap yard (0.2) and the proportion of scrap used in a melt (100% for carbon steel and 66% for stainless steel). However, this clearly underestimates the dilution level for some of the larger products. For example, the boat described is a fishing trawler, which would be constructed over a period of time and is unlikely to use steel from only one single melt. The same is the case for concrete reinforcement steel, where a building is unlikely to be constructed using only the product of a single melt. In RP117, it was assumed that 25% of the reinforcement steel contained the cleared scrap, and this factor was therefore applied here to both the boat and reinforcement steel scenarios.

The parameters relating to time spent on different tasks (with the exception of the truck driver), dust concentrations in the air, breathing rates and dust ingestion rates in RP117 are reasonable for Sweden. However, the data for the physical change in concentration for radionuclides that redistribute into the slag or dust fractions in Sweden are very different from those in RP117, since the reported amounts of dust and slag formed differ significantly. Therefore, it was necessary to adjust the inhalation and ingestion doses for the steelworks to account for both the differences in the proportion of cleared scrap at the steelworks and the differences in the physical concentration effect for radionuclides that redistribute into dust.

For ^{3}H in the Steel plant (Atmos) scenario, it was necessary to estimate the maximum activity of ^{3}H that could be released from the stack in Sweden. The maximum activity comes from the carbon steel plant, due to the lower level of dilution (since more carbon steel is cleared each year than stainless steel), and for 2600 tonnes of 1 Bq/g scrap is 2.6×10^{9} Bq.

For the slag and dust disposal scenarios, the doses are affected by the fraction of cleared scrap processed at the steel works, the physical concentration effect for radionuclides that redistribute into these fractions, and the proportion of material at the landfill that comes from the steelworks. The sizes of the landfills receiving the different wastes have not been confirmed for Sweden, because the relevant by-products are sold for re-use as a construction material or for extraction of value metals prior to landfilling. This suggests that the doses for a landfill worker would be significantly reduced, and working with a stockpile or transporting the slag and dust are likely to be the more important exposure scenarios. However, the related EAF dust-dump trailer scenario (NUREG 1640) gave similar doses to the landfill worker as seen here, and so the scenario still represents a reasonable way of assessing exposure to the handling of the dust.

For the slag and dust disposal scenarios in RP117, the stainless steel slag and carbon steel dust were used to calculate doses, as they were slightly less diluted than the carbon steel slag and stainless steel dust, respectively (Table 16). Using the Swedish data together with the RP117 assumption that a landfill receives 50 000 or 150 000 tonnes of waste per year, suggests that dust and slag from carbon steel will be less diluted than from stainless steel in Sweden (Table 16). Therefore, the doses in RP117 were adjusted accordingly by a factor of 1.3 (slag) or 0.58 (dust) to be representative for the overall difference in dilution between the two studies.

Table 15 Comparison of the parameters used in RP117 and those adapted for Sweden

Parameter	Sweden (this study)	RP117	Adjustment of the relevant RP117 doses to Swedish conditions
Steel			
Fraction of cleared scrap transported	1 (500 hours – 2 hours per 15 tonnes).	1; (but 100 hours per year)	5 x RP117 dose
Fraction of cleared scrap handled at the scrap yard	0.2	0.01	20 x RP117 dose
Fraction of cleared scrap processed at the steel works (and therefore also in the dust and slag scenarios)	Max 0.007 (carbon steel) Max 0.001 (stainless steel)	0.01 0.01	0.7 x RP117 dose 0.1 x RP117 dose
Maximum activity of 3H released at the stack	2.6 x 10^9 Bq	4 x 10^9 Bq	0.7 x RP117 dose
Increased concentration in slag	10 (carbon steel) 3 (stainless steel)	6.7 (carbon steel) 50 (stainless steel)	1.5 x RP117 dose 0.06 x RP117 dose
Increased concentration in dust	50 - 830 (carbon steel) 50 (stainless steel)	67 (carbon steel) 670 (stainless steel)	12 x RP117 dose 0.07 x RP117 dose
Fraction in carbon steel products: Large machine Boat Concrete reinforcement bars Radiator	 0.2 0.05 0.05 0.2	 0.1 0.1 0.025 0.1	 2 x RP117 dose 0.5 x RP117 dose 2 x RP117 dose 2 x RP117 dose
Fraction in stainless steel products: Professional kitchen Process vessel	 0.13 0.13	 0.2 0.2	 0.66 x RP117 dose 0.66 x RP117 dose
Fraction of slag in the landfill	0.7 (carbon steel) 0.9 (stainless steel)	0.4 (carbon steel) 0.08 (stainless steel)	See text and Table 16
Fraction of dust in the landfill	0.008 (carbon steel) 0.2 (stainless steel)	0.12 (carbon steel) 0.006 (stainless steel)	See text and Table 16
Copper			
Fraction of scrap handled at the scrap yard	0.004 (cleared copper in the scrap yard 70/ 20 000)	0.01	0,4 x RP117 dose
Fraction of material processed at the copper refinery, and therefore also in the dust and slag scenarios	0.002	0.01	0,2 x RP117 dose
Fraction in copper products: Musical instrument, kitchen fitting, decorative object, laboratory object Pig meat	 0.01 0.01	 0.3 0.2	 0.033 x RP117 dose 0.033 x RP117 dose
Increased concentration in slag	1.5 (500 000 t from 760 000 t)	2.3	0.7 x RP117 dose
Increased concentration in dust	1900 (400 t from 760 000 t)	100	19 x RP117 dose
Fraction of slag in the landfill	No information	0.18	No change
Fraction of dust in the landfill	No information		No change
Aluminium			
Fraction of scrap handled at the scrap yard	Max 0.03 (fuel enrichment; 500/20000) Max 0.0008 (reactor; 15/20 000)	0.1 (fuel enrichment) 0.01 (reactor)	0.3 x RP117 dose 0.08 x RP117 dose
Fraction of material processed at the aluminium refinery, and therefore also in the dust and slag scenarios	0.007 (fuel enrichment; 500/70000) 0.0002 (reactor; 15/70 000)	0.1 (fuel enrichment) 0.01 (reactor)	0.07 x RP117 dose 0.02 x RP117 dose
Fraction in aluminium products	0.2 (dilution in the scrap yard)	0.2	No change
Increased concentration in slag	5	4.4	1.1 X RP117 dose
Increased concentration in dust	?	480	No change

Table 16 Evaluation of the proportional change in radionuclide concentrations in the dust and slag scenarios

	RP117		Sweden	
	Carbon steel	**Stainless steel**	**Carbon steel**	**Stainless steel**
Dilution steelworks	0.01	0.01	0.007	0.001
Increased conc in slag	6.7	50	10	3
Increased conc in dust	67	670	830	50
Mass slag in landfill (tonnes)	60 000	4000	36000	140000
Fraction slag in landfill	0.4	0.08	0.72	0.93
Mass dust in landfill (tonnes)	6000	300	400	10000
Fraction dust in landfill	0.12	0.006	0.008	0.2
Slag: Proportional change in radionuclide concentration	0.027	**0.040**	**0.050**	0.0028
Dust: Proportional change in radionuclide concentration	**0.080**	0.040	**0.046**	0.01

5.2. Radionuclide distribution during melting

The distribution of radionuclides into the metal, slag and dust during melting clearly affects the dose delivered in each scenario and the scenarios that are most important. The radionuclide distribution data applied in RP117 are presented but not justified, and these are given in Appendix C of the current report. To account for uncertainties in the radionuclide distribution during melting, the study allowed the sum of the distribution of some radionuclides in the metal, slag and dust to exceed one, i.e. some radionuclides are accounted for in more than one fraction.

The distribution data applied in NUREG 1640 and US EPA (2001) also allowed for uncertainties in the distribution data and were generally in good agreement with the data used in RP117. However, there were also a significant number of cases when the RP117 data were highly conservative, and applied a distribution factor of 1 for the radionuclide in both the metal and the slag, or when there was poor agreement. The high degree of conservatism was noted in the very different most restrictive copper exposure pathways identified for $^{90+}$Sr in RP117 (metal – musical instrument) and NUREG 1640 (handling slag). However, after the rounding procedure, the $^{90+}$Sr clearance levels defined by steel and copper scenarios were the same, thus the final clearance level was not affected by this conservatism. Furthermore, the majority of the cases where RP117 was highly conservative involved copper or aluminium processing while steel scenarios were most restrictive for the majority of radionuclides. The more fundamental differences in the distribution data for the radionuclides relevant to Swedish nuclear sites are shown in Table 17. The copper distributions shown for US EPA 2001 and NUREG 1640 are for the one of the stages in copper refining, the fire-refining stage, which was included in their scenario analyses. They also reported the distributions during electrolytic refining, into the copper cathode, anode slime and electrolyte bleed, but these were not considered in their scenario analyses and are not included here.

Table 17 Contrasting radionuclide distributions in RP117, US EPA 2001 and NUREG 1640. The data that affect the most restrictive scenario are given in bold

Element	Metal processed	Proportional distribution after melting								
		RP117			US EPA 2001			NUREG 1640		
		Metal	Slag	Dust	Metal	Slag	Dust/gas	Metal	Slag	Dust/gas
C	**Steel**	**0**	**0**	**1**	**1-0.27**	**0**	**0-0.73**	**1-0.27**	**0**	**0-0.73**
C	Aluminium	0	0	1	0.01-0.1	0.99-0.9	0	0.01-0.5	0.99-0.5	0
Mn	**Steel**	**1**	**0.1**	**0.05**	**0.24-0.66**	**0.72-0.33**	**0.03-0.04**	**0.02-0.24**	**0.95-0.72**	**0.03-0.04**
Ru	**Steel**	**0.1**	**0.1**	**1**	**0.99**	**0**	**0.01**	**0.985-0.995**	**0**	**0.005-0.015**
Ru	Copper	0.1	0.1	1	1	0	0	1	0	0
Ru	Aluminium	0.1	0.1	1	1	0	0	1	0	0
Sb	Copper	1	0.2	0.2	0.08-0.25	0.75-0.92	0 – 0.05	0.1-0.69	0.31-0.94	0-0.05
Tc	Steel	0.1	1	0.001	0.99	0	0.01	0.985-0.995	0	0.005-0.015
Tc	Aluminium	0.1	1	0.001	1	0	0	1	0	0

For ^{54}Mn there was a notable variation in the material delivering the highest normalised doses between the three studies (Table 9) and the distribution data shows that firstly it partitions into both the metal and the slag, and that there is some variation in the assumed distribution between the different studies. There are also variations between the steel-melting distribution data for C, Ru and Tc, which will impact the dose calculations to varying extents. US EPA (2001) provided a literature review of radionuclide distributions during melting, giving more confidence in the distributions they applied, and very similar distributions were applied for these elements in the later NUREG 1640 study. In brief:

- Carbon is added during the steel making process making it difficult to predict losses of ^{14}C from the melt. The extent of loss from the melt depends on the C content of the scrap, the C added and desired C content of the finished product. It is therefore advisable to include this uncertainty in the distribution data.
- Technetium is difficult to remove from the melt during steel recycling since the free energy of oxide formation is less negative than for Fe oxides (Warren and Clark 1995 (JAERI), presenting data from Copeland 1978, US EPA 2001), and therefore remains in the metal.
- Ruthenium is also expected to remain in the ingot based on free energy of its oxide formation, which is less negative than for iron oxides (see fig in Warren and Clark 1995 (JAERI)). Therefore the volatility of Ru(VII) oxide should not be an issue in iron melts.

The literature therefore suggests that the Ru and Tc data applied in RP117 can be improved and that it is also possible for ^{14}C to remain in the steel.

The following decisions were therefore made in terms of the necessary adjustments of the RP117 dose calculations related to radionuclide distributions:

- ^{14}C in the dust is far more important than ^{14}C that remains in the steel in terms of the dose consequences from this relatively low energy beta emitter. Since the majority of the ^{14}C could be in the dust (EPA 2001) and RP117 assumes all of the ^{14}C is in the dust, the doses calculated cover the main exposure pathways and no adjustment was made to the distribution.
- 1% of the ^{99}Tc and ^{106}Ru were considered to be present in the steel slag and dust, and 100% in the metal
- The maximum proportion of ^{54}Mn in the steel slag was increased 10-fold to 100%
- The possible distribution of Sb during copper melting was changed to 100% copper; 100% slag; 20% dust

- The possible distribution of Ru in the metal after copper melting was changed to 100% (distribution into slag and dust unchanged)
- The possible distribution of Tc and Ru in the metal after aluminium melting was increased to 100% (distribution into slag and dust unchanged)

5.3. Dose coefficients

The dose coefficients applied in RP117 were compared with the most recent values, published in IAEA (2014). The majority of dose coefficients for the radionuclides included in this study were the same, and the exceptions are given in Table 18. Note that the ingestion and inhalation dose coefficients for workers can be slightly different from those for adult members of the public because they reflect exposure to particles of different activity median aerodynamic diameters. The term worker is used to mean all people at work, not just radiation workers.

Table 18 Ratio of dose coefficients RP117/IAEA (2014) where they differ for the radionuclides included in this study

		Sr-90+	Sb125+	U238+	Zr-95+
INGESTION (PUBLIC)	adult	1.10	1.18	1.09	1.61
	child – 10 y	1.10	1.20	1.12	1.58
	baby – 1 y	1.27	1.24	1.23	1.57
INHALATION (PUBLIC)	adult	1.01	1.08	1.00	1.30
	child – 10 y	1.02	1.08	1.00	1.30
	baby – 1 y	1.02	1.08	1.00	1.31
INGESTION (WORKER)	adult	1.10	1.18	1.09	1.66
INHALATION (WORKER)	adult	1.02	1.20	1.00	1.83

Where the value differed by 10% or more, it was adjusted in the calculations to the value in IAEA (2014).

5.4. Scrap cutting scenario

As discussed in Section 4.2.1, RP117's scrap cutting scenario does not obviously describe the situation in Swedish recycling centres. New scenarios have therefore been developed based on the method in NUREG 1640 and US EPA (2001), which assumed that the radionuclide concentration of the dust is the same as in the metal. Here, the dust concentrations are set at 60% of the maximum allowable respirable dust concentrations in the workplace throughout the working year and the IAEA (2014) worker dose coefficients were applied. Since ingestion doses could also be important, these were calculated on the basis of the inadvertent ingestion of 0.15 g dust/day, consistent with other workplace ingestion rates in RP117 and the maximum applied in NUREG 1640 (0.02 g/h).

Table 19 Parameters applied to assess the doses during scrap cutting in this study

Parameter	Value
Mean breathing rate ($m^3\ h^{-1}$)	1.2
Inhalable particle concentration in the atmosphere ($g\ m^{-3}$)	3×10^{-3}
Time of exposure ($h\ y^{-1}$)	1800
Fraction of VLLW	0.2
Specific concentration factor in the dust	1
Inadvertent dust ingestion (g/day)	0.15

The inhalation scenario leads to doses that were higher than the RP117 scrap cutting inhalation doses, but lower than the doses that would arise if the RP117 scrap cutting doses were adjusted for the higher proportion of cleared scrap in Sweden (20% of the scrap handled rather than 1%).

5.5. Products based on other metals

Some of the by-products of copper recycling in Sweden are metals or metal salts that have radioactive isotopes that may be present in cleared scrap from nuclear sites. Boliden, for example, produces nickel sulphate, metallic silver and zinc oxide (zinc clinker), which would be expected to contain the ^{59}Ni and ^{63}Ni, $^{108m+}$Ag and $^{110m+}$Ag, and ^{65}Zn, respectively. Movement from the scrap into the by-products could in some situations result in a significant increase in the concentration of these isotopes. However, at Boliden, where large masses of copper are recycled each year, the mass of each of these products well exceeds the mass of copper scrap assumed to be cleared from the decommissioning of a nuclear power plant (70 tonnes/year). Since this is the most likely destination for copper in Sweden, there is no concern that copper by-products above the clearance level could be created.

Table 20 Mass of metal products produced during copper recycling

By-product	Mass produced per year (tonnes)
Nickel sulphate	2 500
Metallic silver	347
Zinc oxide	26 000

6. Suitability of the BSS clearance levels for metal recycling in Sweden

6.1. Comparison of the most restrictive scenarios in RP117 and in this study

The metal recycling scenarios of RP117/RP89 have been adjusted to account for differences in the processes applied in Sweden, as described in Chapter 5. Some scenarios were removed, as they were not considered relevant for Sweden (Steel scenarios: Player (INH) and Spectator (INH)), the scrap cutting scenario was recalculated using a different approach, and some of the other adjustments were also substantial. As a result, the scenario that delivered the maximum dose changed for many radionuclides (Table 21). The general importance of the copper and aluminium scenarios decreased, since most of the relevant parameters for Sweden led to greater dilution of the cleared scrap than assumed in RP117. The exceptions to this are the aluminium Fishing boat scenario, which became the most restrictive for ^{57}Co as the dilution in the steel Boat scenario doubled, and the Copper smelting – dust (INH) scenario, which became the most restrictive scenario for Ni-isotopes due to the greater concentration effect in the dust during processing (lower mass of dust formed per tonne of copper processed).

The Scrap cutting (INH) scenario for Sweden was based on a different set of assumptions from those in RP117 Scrap cutting (INH) scenario. The approach here assumed that the radionuclide concentration of the dust was the same as the scrap metal (as also applied in US EPA (2001) and NUREG 1640), and the dust level was selected to reflect 60% of the maximum permissible dust concentration in a workplace. This approach allowed inclusion of all radionuclides considered in this study (Section 5.4), and the inclusion of a Scrap cutting (ING) scenario assuming the same dust ingestion rate as in the other dust ingestion scenarios. Together with the other changes, these scenarios became the most restrictive for a large number of radionuclides in Sweden (inhalation: 9; ingestion: 2). However, for many of the relevant radionuclides, the maximum doses received for the new inhalation pathway were very similar to those in RP117's Player (INH) scenario.

The increase in the maximum time spent transporting cleared scrap in Sweden meant that it also became an important exposure pathway for eight medium to high energy gamma emitters. All radionuclides resulting in the greatest exposures in the Dust L. AF W (EXT) scenario in RP117 were also restricted by this scenario in Sweden, although the actual dose received in this scenario decreased by 40%. The same is true for radionuclides by Slag L. IF W (EXT), although in this case the doses are 30% higher in Sweden. The change in the amount of ^{3}H released influenced the dose received but did not alter the most restrictive scenario. The change in scenario for ^{14}C and $^{109+}$Cd from Steel plant IF (ING) to Steel plant ARC (ING) reflects the difference in the physical concentration factors applied for carbon steel (ARC in RP117) and stainless steel (IF in RP117) in the two studies. The Swedish data showed that less dust forms during the smelting of carbon steel scrap than considered in RP117 (i.e. there is a greater concentration effect), while for stainless steel the opposite was the case. Changes to the internal dose coefficients did not have a visible effect, since external exposure was most important for $^{90+}$Sr, $^{125+}$Sb and $^{95+}$Zr, and the scenario with the maximum exposure to $^{238+}$U involved a different metal.

For most radionuclides, the maximum doses calculated for Sweden were within the range 0.5 – 2.8 of the RP117 maximum doses. Therefore the difference was quite limited for the majority of radionuclides considered. Technetium-99 showed the greatest difference in maximum dose between RP117 and this study, and this reflects the changes to the distribution during melting, so that only a small proportion (1%) is assumed to be associated with the slag. The most restrictive scenario for ^{99}Tc in Sweden is the new Scrap cutting (ING) scenario. Iron-55 showed the next greatest deviation, and this was also a result of the introduction of the Scrap cutting (ING) scenario. Nickel-63 also gave a more elevated dose, reflecting the higher concentration in the dust due to the lower mass of dust formed during copper processing. Copper is mainly in the form of copper cables and both RP117 and this study assumed that the copper is cleared after the insulation material has been removed. It is, however, likely that the cables are cleared intact in Sweden and surface contamination will be removed when the insulation is stripped away. However, removal of activity with the insulation is not taken into account in the scenarios.

Table 21 Most restrictive scenarios in RP117 and for Sweden (this study)

	RP117		**Sweden**			
	Most restrictive scenario	Metal	Most restrictive scenario	Metal	Maximum dose (Sv/year)	Ratio of maximum doses: Sweden/ RP117
Ag-108m+	Boat AF (EXT)	Steel	Transport (EXT)	Steel	2.11E-05	1.7
Ag-110m+	Boat AF (EXT)	Steel	Transport (EXT)	Steel	4.18E-05	2.1
Am-241	Player IF (INH)	Steel	Scrap cutting (INH)	Steel	3.51E-05	1.1
C-14	Steel plant IF (ING)	Steel	Steel plant ARC (ING)	Steel	1.14E-07	0.9
Cd-109+	Steel plant IF (ING)	Steel	Steel plant ARC (ING)	Steel	3.93E-07	0.9
Ce-144+	Slag L. IF W (EXT)	Steel	Slag L. IF W (EXT)	Steel	1.23E-06	1.3
Cm-244	Player IF (INH)	Steel	Scrap cutting (INH)	Steel	2.21E-05	1.2
Co-57	Boat AF (EXT)	Steel	Aluminium fishing boat (EXT)	Aluminium	3.32E-07	0.5
Co-58	Boat AF (EXT)	Steel	Transport (EXT)	Steel	1.41E-05	1.9
Co-60	Boat AF (EXT)	Steel	Transport (EXT)	Steel	4.33E-05	2.5
Cs-134	Dust L. AF W (EXT)	Steel	Dust L. AF W (EXT)	Steel	2.80E-05	0.6
Cs-137+	Dust L. AF W (EXT)	Steel	Dust L. AF W (EXT)	Steel	1.01E-05	0.6
Eu-152	Slag L. IF W (EXT)	Steel	Slag L. IF W (EXT)	Steel	2.82E-05	1.3
Eu-154	Slag L. IF W (EXT)	Steel	Slag L. IF W (EXT)	Steel	2.50E-05	1.3
Eu-155	Slag processing (EXT)	Aluminium	Slag L. IF W (EXT)	Steel	1.89E-07	0.6
Fe-55	Steel plant IF (ING)	Steel	Scrap cutting (ING)	Steel	2.21E-09	5.9
H-3	Steel plant (Atmos)	Steel	Steel plant (Atmos)	Steel	5.11E-09	0.7
K-40	Dust L. AF W (EXT)	Steel	Dust L. AF W (EXT)	Steel	3.25E-06	0.6
Mn-54	Boat AF (EXT)	Steel	Slag L. IF W (EXT)	Steel	1.72E-05	2.8

	RP117		**Sweden**			
	Most restrictive scenario	Metal	Most restrictive scenario	Metal	Maximum dose (Sv/year)	Ratio of maximum doses: Sweden/ RP117
Na-22	Dust L. AF W (EXT)	Steel	Dust L. AF W (EXT)	Steel	4.00E-05	0.6
Nb-94	Slag L. IF W (EXT)	Steel	Slag L. IF W (EXT)	Steel	3.22E-05	1.3
Ni-59	Musical instrument (SKIN)	Copper	Copper smelting – dust (INH)	Copper	1.08E-09	2.1
Ni-63	Refining (INH)	Copper	Copper smelting – dust (INH)	Copper	2.56E-09	3.8
Pu-238	Player IF (INH))	Steel	Scrap cutting (INH)	Steel	3.90E-05	1.1
Pu-239	Player IF (INH)	Steel	Scrap cutting (INH)	Steel	4.16E-05	1.0
Pu-240	Player IF (INH)	Steel	Scrap cutting (INH)	Steel	4.16E-05	1.0
Pu-241	Player IF (INH)	Steel	Scrap cutting (INH)	Steel	7.54E-07	1.0
Ru-106+	Dust L. AF W (EXT)	Steel	Transport (EXT)	Steel	6.75E-06	1.0
Sb-124	Slag processing (EXT)	Aluminium	Transport (EXT)	Steel	3.03E-05	1.4
Sb-125+	Boat AF (EXT)	Steel	Transport (EXT)	Steel	4.88E-06	1.6
Sc-46	Slag L. IF W (EXT)	Steel	Slag L. IF W (EXT)	Steel	4.33E-05	1.3
Sn-113+	Dust L. AF W (EXT)	Steel	Dust L. AF W (EXT)	Steel	3.54E-06	0.6
Sr-90+	Musical instrument (EXT effective)	Copper	Transport (EXT)	Steel	1.54E-06	1.4
Tc-99	Slag L. IF Child	Steel	Scrap cutting (ING)	Steel	5.23E-09	0.02
U-234	Slag processing (INH) (AG3)	Aluminium	Scrap cutting (INH)	Steel	8.84E-06	1.4
U-235+	Slag processing (EXT) (AG3)	Aluminium	Scrap cutting (INH)	Steel	7.93E-06	0.6
U-238+	Slag processing (INH) (AG3)	Aluminium	Scrap cutting (INH)	Steel	7.41E-06	1.4
Zn-65	Dust L. AF W (EXT)	Steel	Dust L. AF W (EXT)	Steel	1.09E-05	0.6
Zr-95+	Slag processing (EXT)	Aluminium	Transport (EXT)	Steel	2.15E-05	1.2

6.2. Comparison of metal recycling clearance levels from this study with those in RP89 and the general clearance levels in BSS (2013)

The maximum doses calculated in the Swedish scenarios for the clearance of scrap metal with 1 Bq/g contamination have been converted into 10 µSv/year clearance levels (Table 22). These were then rounded up or down according to the procedure described in Section 1.1 for comparison with the BSS (2013) and RP89 clearance levels.

The results show that the rounded clearance levels derived are equal to or higher than the general clearance levels in BSS (2013) for all radionuclides considered in this study. This means that, despite the differences in many of the parameters applied in RP117 and this study, application of the BSS (2013) clearance levels would limit the exposure of the Swedish public to below the desired level.

Comparison of the rounded clearance levels derived in this study with the levels recommended in RP89 shows a more variable situation. The rounded clearance levels are the same for 24 of the radionuclides, while those derived for Sweden are higher for 5 radionuclides and lower for 10 radionuclides. The reason behind 6 of the lower clearance levels in Sweden (for ^{241}Am, ^{22}Na, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{46}Sc) is that the clearance levels derived in RP117 for these radionuclides were increased to 1 Bq/g for recommendation in RP89, because of the small quantities expected in cleared scrap metal. Assuming that the quantities of these six radionuclides will also be small in scrap cleared in Sweden, the RP89 clearance levels for these six radionuclides are also acceptable in Sweden. RP89 also increased the clearance level for ^{134}Cs to 1 Bq/g, the clearance level calculated in this study. The change in clearance level for ^{94}Nb was somewhat arbitrary as the maximum dose received only increased by 30%. However, the change for $^{110m+}$Ag, ^{60}Co and $^{125+}$Sb reflects that the time transporting cleared scrap is considered to be longer in Sweden than assumed in RP117. The raw clearance levels derived in RP117 and this study are compared in Appendix D.

Table 22 Comparison of the clearance levels for scrap recycling in Sweden with the general clearance levels in BSS and the scrap clearance levels in RP89.

	Clearance level this study - raw	Clearance level this study - rounded	Rounded clearance level this study/BSS (2013)	Rounded clearance level this study/RP89
Ag-108m+	0.48	1	Not given in BSS	1
Ag-110m+	0.24	0.1	1	0,1
Am-241	0.28	0.1	1	0,1*
C-14	88	100	100	1
Cd-109+	25	10	10	1
Ce-144+	8.2	10	10	1
Cm-244	0.45	1	1	1
Co-57	30	100	100	10
Co-58	0.71	1	1	1
Co-60	0.23	0.1	1	0,1
Cs-134	0.36	1	10	1*
Cs-137+	0.99	1	10	1
Eu-152	0.35	1	10	1
Eu-154	0.40	1	10	1
Eu-155	53	100	100	10
Fe-55	4500	10000	10	1
H-3	2000	1000	10	1
K-40	3.1	10	1	10
Mn-54	0.58	1	10	1
Na-22	0.25	0.1	1	0,1*
Nb-94	0.31	0.1	1	0,1
Ni-59	9200	10000	100	1
Ni-63	3900	10000	100	1
Pu-238	0.26	0.1	1	0,1*
Pu-239	0.24	0.1	1	0,1*
Pu-240	0.24	0.1	1	0,1*
Pu-241	13	10	1	1
Ru-106+	1.5	1	10	1
Sb-124	0.33	1	1	1
Sb-125+	2.1	1	10	0,1
Sc-46	0.23	0.1	1	0,1*
Sn-113+	2.8	1	1	10
Sr-90+	6.5	10	10	1
Tc-99	1900	1000	1000	10
U-234	1.1	1	1	1
U-235+	1.3	1	1	1
U-238+	1.4	1	1	1
Zn-65	0,92	1	10	1
Zr-95+	0,47	1	1	1

*clearance level increased to 1 Bq/g in RP89 due to the small quantities expected in scrap metal

7. References

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Appendix A. Radionuclides reported in the clearance produce at the nuclear facilities and the detection limits included in the clearance calculations

Radio-nuclide	Forsmark		Oskarshamn		Ringhals		SVAFO - R2	
	Direct/ Vector	Detection limit reported if not detected	Direct	Detection limit reported if not detected	Direct	Detection limit reported if not detected	Direct	Detection limit reported if not detected*
Ac-228					D			
Ag-108m	v		D		D		D	MDA/2
Ag-110m	v		D	X	D	X	D	MDA/2
As-76	v							
Am-241*			v				D	
Am-243*			v					
Ba-131			D					
Ba-133					D			
Ba-140	v		D		D			
C-14			v				v	
Cd-109							D	MDA/2
Ce-141			D		D			
C-143	v							
Ce-144			D		D		D	MDA/2
Cl-36							v	
Cm-242			v					
Cm-243			v					
Cm-244			v				v	
Co-57			D		D		D	MDA/2
Co-58	v		D		D	X		
Co-60	D	X	D	X	D	X	D	
Cr-51	v		D		D	X		
Cs-134			D		D		D	MDA/2
Cs-136			D		D			
Cs-137	D		D	X	D	X	D	
Eu-152					D		D	MDA/2
Eu-154							D	MDA/2
Eu-155							D	MDA/2
Fe-55					v		v	
Fe-59			D		D	X		
H-3*			v				D	
Hf-181			D					
I-129*			v					
I-131	v		D		D			
K-40					D			
La-140	v				D			
Mn-54	v		D	X	D	X	D	MDA/2

Radio-nu-clide	Forsmark		Oskarshamn		Ringhals		SVAFO - R2	
	Direct/ Vector	Detection limit re-ported if not detected	Direct	Detection limit re-ported if not detected	Direct	Detection limit re-ported if not detected	Direct	Detection limit re-ported if not detected*
Mo-99	v							
Na-22					D		D	MDA/2
Nb-94							D	MDA/2
Nb-95			D		D			
Ni-59*			v					
Ni-63*			v		v		v	
Np-237							v	
Np-239	v		D					
Pu-238			v				v	
Pu-239			v				v	
Pu-240			v				v	
Pu-241							v	
Pu-242							v	
Ru-103					D			
Ru-106					D		D	MDA/2
Sb-122	v							
Sb-124	v		D		D	X		
Sb-125			D		D		D	MDA/2
Sc-46					D			
Sn-113			D		D			
Sr-90	v		v				v	
Ta-182	v							
Tc-99			v*				v	
Te-132	v							
U-234							v	
U-235			D				D	MDA/2
U-238							D	
Y-91								
Zn-65			D	X	D			
Zr-95	v				D	X		

Appendix B. Scenarios for the assessment of public exposure from the recycling of cleared metals from nuclear installations in the USA (NUREG 1640)

The pathways selected for analysis included external exposure, inhalation of dust, inadvertent ingestion of particulate matter, and ingestion of food and water.

Steel scenario abbreviation	Steel scenario title	Copper scenario abbreviation	Copper scenario title	Aluminium scenario abbreviation	Aluminium scenario title
Handling and Processing					
Scrap yard	Processing steel scrap at scrap yard	Scrap yard	Processing copper scrap at scrap yard	Scrap yard	Processing aluminium scrap at scrap yard
Handling slag	Handling slag at steel mill	Handling slag	Handling copper slag at fire-refining facility	Handling dross	Handling dross at secondary smelter
Transferring EAF dust	Transferring EAF dust at steel mill				
Baghouse maintenance	EAF Baghouse maintenance	Baghouse maintenance	Reverberatory fumace baghouse maintenance	Baghouse maintenance	Baghouse maintenance at secondary smelter
Handling metal product	Handling metal product at steel mill or foundry	Handling metal product	Handling fire-refined copper product	Handling metal product	Handling metal product at secondary smelter
Processing EAF dust	Processing EAF dust				
Processing steel slag	Processing steel slag for road construction				
Atmospheric Release					
Airbome emissions	Emission of airbome effluents from fumace	Airborne emissions	Emission of airbome effluents from fumace	Airbome emissions	Emission of airbome effuents from smelter
Transportation					
Scrap truck-driver	Truck driver hauling cleared steel scrap	Scrap truck-driver	Truck driver hauling cleared copper scrap	Scrap truck-driver	Truck driver hauling cleared aluminum scrap
Slag truck-driver	Truck driver hauling slag	Slag truck-driver	Truck driver hauling reverberatory fumace slag	Dross truck-driver	Truck dver hauling dross from smelter
EAF dust-bulk trailer	Truck driver hauling EAF dust in dry bulk trai	Dust truck-driver	Truck driver hauling reverberatory furnace dust Fe	Dust truck-driver	Truck driver hauling dust from smelter
EAF dust-dump trailer	Truck driver hauling EAF dust in dump trailer				
Metal product-driver	Truck driver hauling steel products	Metal product-driver	Truck driver hauling fire-refined copper	Metal product-driver	Truck driver hauling metal product from smelter
Product Use					
Sailor-operations	Sailor with watch station in operations area				
Sailor-deck duty	Sailor with watch station on deck				
Building road with slag	Building road using steel slag				
Driving on slag road	Driving on road built with steel slag				
Slag basement	Living in basement built with cement made from slag				
Exposure to large mass	Exposure to large metal mass			Exposure to large mass	Exposure to large metal mass
Exposure to small mass	Exposure to small metal mass	Exposure to small mass	Exposure to small mass of fire-refined copper	Exposure to small mass	Exposure to small metal mass
Steel object on body	Small steel object on body	Copper object on body	Small fire-refined copper object on body		

Home with steel studs	Living in home built with steel studs				
Driver-automobile	Driver of automobile with cast iron engine block			Driver-engine block	Driver of taxi with aluminum engine block
Driver-diesel engine	Driver of truck with cast iron diesel engine block				
Sailor-hull plate	Sailor berthing near steel hull plate				
		Drinking-copper pipes	Drinking tapwater from copper pipes		
				Aluminum cookware	Use of aluminum cooking ware
Landfill Disposal					
Scrap disposal-industrial	Handling steel scrap at an industrial landfill	Scrap disposal-industrial	Handling copper scrap at industrial landfill	Scrap disposal-industrial	Handling aluminum scrap at industrial landfill
Scrap disposal-municipal	Handling steel scrap at a municipal landfill	Scrap disposal-municipal	Handling copper scrap at municipal landfill	Scrap disposal-municipal	Handling aluminum scrap at municipal landfill
Dust disposal-industrial	Handling BOF/foundry dust at an industrial landfill				
Dust disposal-municipal	Handling BOF/foundry dust at a municipal landfill				
Slag disposal-industrial	Handling slag at an industrial landfill	Slag disposal-industrial	Handling copper slag at industrial landfill	Dross disposal-industrial	Handling dross at industrial landfill
Slag disposal-municipal	Handling slag at a municipal landfill	Slag disposal-municipal	Handling copper slag at municipal landfill	Dross disposal-municipal	Handling dross at municipal landfill
EAF dust disposal	Handling EAF dust at a hazardous waste landfill				
Groundwater Infiltrated by Leachate from Landfills or Storage Piles					
Leachate-industrial-scrap	Leachate from industrial landfill-scrap	Leachate- industrial- scrap	Leachate from industrial landfill-scrap	Leachate-industrial-scrap	Leachate from industrial landfill-scrap
Leachate-municipal-scrap	Leachate from municipal landfill-scrap	Leachate-municipal-scrap	Leachate from municipal landfill-scrap	Leachate-municipal-scrap	Leachate from municipal landfill-scrap
Leachate-industrial-dust	Leachate from industrial landfill-BOF/foundry dust				
Leachate-municipal-dust	Leachate from municipal landfil-BOFfoundry dust				
Leachate-steel slag	Leachate from slag storage pile				
		Leachate-industrial-dross	Leachate from industrial landfill-slag	Leachate-industrial-dross	Leachate from industrial landfill-dross
		Leachate-municipal-dross	Leachate from municipal landfill-slag	Leachate-municipal-dross	Leachate from municipal landfill-dross

Appendix C. Distribution of radionuclides during melting of steel, copper and aluminium applied in RP117

Nuclide	RADIONUCLIDE DISTRIBUTION FACTOR, r (FRACTION)								
	r(STEEL)			r(COPPER)			r(ALUMINIUM)		
	Ingot	Slag	Dust	Ingot	Slag	Dust	Ingot	Slag	Dust
H-3	0	0	1	0	0	1	0	0	1
C-14	0	0	1	0	0	1	0	0	1
Mn-54	1	0.1	0.05	0.010	1	0.05	1	0.2	0.005
Fe-55	1	0.010	0.005	0.010	1	0.05	1	0.2	0.005
Co-60	1	0.010	0.005	0.05	1	0.2	1	0.1	0.001
Ni-59	1	0.010	0.001	0.05	1	0.2	1	0.2	0.005
Ni-63	1	0.010	0.001	0.05	1	0.2	1	0.2	0.005
Zn-65	0.1	0.1	1	0.010	1	0.5	1	0.05	0.005
Sr-90	0.1	1	0.1	1	1	0.1	1	1	0.1
Nb-94	0.1	1	0.001	1	1	1	1	1	1
Tc-99	0.1	1	0.001	0.1	1	0.001	0.1	1	0.001
Ru-106	0.1	0.1	1	0.1	0.1	1	0.1	0.1	1
Ag-108m	1	0.010	0.1	1	1	0.1	1	0.05	0.001
Ag-110m	1	0.010	0.1	1	1	0.1	1	0.05	0.001
Sb-125	1	0.001	0.010	1	0.2	0.2	1	1	0.002
Cs-134	0.001	0.1	1	0.1	1	1	0.010	1	1
Cs-137	0.001	0.1	1	0.1	1	1	0.010	1	1
Eu-152	0.001	1	0.001	0.5	1	0.001	0.5	1	0.001
Eu-154	0.001	1	0.001	0.5	1	0.001	0.5	1	0.001
U-234	0.1	1	0.001	1	1	0.001	0.5	1	0.001
U-235	0.1	1	0.001	1	1	0.001	0.5	1	0.001
U-238	0.1	1	0.001	1	1	0.001	0.5	1	0.001
Pu-238	0.1	1	0.001	1	1	0.001	0.5	1	0.001
Pu-239	0.1	1	0.001	1	1	0.001	0.5	1	0.001
Pu-240	0.1	1	0.001	1	1	0.001	0.5	1	0.001
Pu-241	0.1	1	0.001	1	1	0.001	0.5	1	0.001
Am-241	0.1	1	0.001	1	1	0.001	0.5	1	0.001
Cm-244	0.1	1	0.001	1	1	0.001	0.5	1	0.001
Na-22	0.001	0.1	1	0.1	1	1	0.1	1	0.1
K-40	0.001	0.1	1	0.1	1	1	0.1	1	0.1
Sc-46	0.1	1	0.1	1	1	0.1	1	1	0.1
Co-57	1	0.010	0.005	0.05	1	0.2	1	0.1	0.001
Co-58	1	0.010	0.005	0.05	1	0.2	1	0.1	0.001
Zr-95	1	0.010	0.005	1	1	1	1	1	1
Cd-109	0.1	0.1	1	0.010	1	0.5	1	0.05	0.005
Sn-113	0.1	0.1	1	0.1	0.1	1	0.1	1	1
Ce-144	0.1	1	0.1	1	1	0.001	1	1	0.001
Eu-155	0.001	1	0.001	0.5	1	0.001	0.5	1	0.001

Appendix D. Comparison of the raw metal recycling clearance levels in this study and RP89

	Raw clearance level this study	Raw clearance level RP89 (from RP117)	Raw clearance level this study/Raw clearance level RP89
Ag-108m+	0.48	0.82	0.58
Ag-110m+	0.24	0.51	0.47
Am-241	0.28	0.31	0.92
C-14	88	76	1.2
Cd-109	25	22	1.2
Ce-144+	8.2	11	0.77
Cm-244	0.45	0.52	0.87
Co-57	30	15	2.0
Co-58	0.71	1.4	0.51
Co-60	0.23	0.58	0.40
Cs-134	0.36	0.21	1.7
Cs-137+	0.99	0.58	1.7
Eu-152	0.35	0.46	0.77
Eu-154	0.40	0.52	0.77
Eu-155	53	30	1.8
Fe-55	4500	27000	0.17
H-3	2000	1370	1.4
K-40	3.1	1.78	1.7
Mn-54	0.58	1.63	0.36
Na-22	0.25	0.15	1.7
Nb-94	0.31	0.40	0.77
Ni-59	9200	20000	0.47
Ni-63	3900	15000	0.26
Pu-238	0.26	0.27	0.95
Pu-239	0.24	0.25	0.97
Pu-240	0.24	0.25	0.97
Pu-241	13	13	1.0
Ru-106+	1.5	1.4	1.0
Sb-124	0.33	0.46	0.72
Sb-125+	2.1	3.2	0.64
Sc-46	0.23	0.30	0.77
Sn-113+	2.8	1.6	1.7
Sr-90+	6.5	8.9	0.73
Tc-99	1900	39	49
U-234	1.1	1.6	0.73
U-235+	1.3	0.81	1.6
U-238+	1.4	1.8	0.73
Zn-65	0.92	0.53	1.7
Zr-95+	0.47	0.57	0.82

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 300 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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