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Validation of dose calculation programmes for recycling

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SUMMARY: This report describes a validation of the computer codes RESRAD-RECYCLE and CERISE, which are used to estimate radiation doses due to the recycling of scrap metal. Calculated external radiation doses to individuals are compared with measured data from different steps of the processing of slightly contaminated material, mainly in Studsvik, Sweden.

SAMMANFATTNING: Rapporten beskriver en validering av datorprogrammen RESRAD-RECYCLE och CERISE, vilka används för att uppskatta av stråldoser vid återvinning av metaller. Beräknade externa stråldoser jämförs med mätdata från olika hanteringssteg vid behandlingen av kontaminerat skrot, främst i Studsvik.

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Preface

This report contains the results from an international project initiated by the SSI in 1999. The primary purpose of the project was to validate some of the computer codes that are used to estimate radiation doses due to the recycling of scrap metal. The secondary purpose of the validation project was to give a quantification of the level of conservatism in clearance levels based on these codes. Specifically, the computer codes RESRAD-RECYCLE and CERISE were used to calculate radiation doses to individuals during the processing of slightly contaminated material, mainly in Studsvik, Sweden. Calculated external doses were compared with measured data from different steps of the process.

The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the SSI or any other of the participating organisations. The participants, both individual and organisational, do not make any warranty, expressed or implied, or assume any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product, or progress disclosed or discussed in this report, or represent that its use by such third party would not infringe privately owned rights.

The comparison of calculations and measurements shows that the computer code calculations resulted in both overestimations and underestimations of the external doses for different recycling activities. The SSI draws the conclusion that the accuracy is within one order of magnitude when experienced modellers use their programmes to calculate external radiation doses for a recycling process involving material that is mainly contaminated with cobalt-60. No errors in the codes themselves were found. Instead, the inaccuracy seems to depend mainly on the choice of some modelling parameters related to the receptor (e.g., distance, time, etc.) and simplifications made to facilitate modelling with the codes (e.g., object geometry).

Clearance levels are often based on studies on enveloping scenarios that are designed to cover all realistic exposure pathways. It is obvious that for most practical cases, this gives a margin to the individual dose constraint (in the order of 10 microsievert per year within the EC). This may be accentuated by the use of conservative assumptions when modelling the enveloping scenarios. Since there can obviously be a fairly large inaccuracy in the calculations, it seems reasonable to consider some degree of conservatism when establishing clearance levels based on calculations. The parameters used in enveloping scenarios have however not been specifically studied in this report.

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Introduction

For the nuclear industry, the minimisation of the volumes of radioactive waste arising from the refurbishment or decommissioning of nuclear facilities has been a high priority goal. The recycling of very low level radioactive material (or its reuse or disposal) without radiological restrictions, instead of disposal as radioactive waste, has long been identified as a significant means of achieving this aim. For regulators, it is important to develop guidance for recycling that adequately protects human health and the environment. Various international and national bodies such as the International Atomic Energy Agency, the European Commission, the US Nuclear Regulatory Commission have put forward proposals or guidance documents to regulate the 'clearance' of this surplus material from regulatory control, in order to allow its recycling as a material management practice.

All these proposals are based on predicted scenarios for subsequent utilisation of the released materials. The calculation models used in these scenarios tend to utilise conservative data regarding exposure times and dose uptake as well as other assumptions as a safeguard against uncertainties.

Another aspect is common to all these calculation models and codes: none of them has ever been validated by comparison with the actual real life practice of recycling. The Swedish Radiation Protection Institute initiated the Validation Project in order to validate some of the assumptions made in these calculation models, and, thereby, better assess the radiological consequences of recycling on a practical large scale.

The validation was proposed to be carried out by the following chain of operations:

- Two consignments of contaminated scrap, each of about 30 tons, were to be melted at Studsvik RadWaste, Sweden.
- Ingots resulting from this melting, which have decayed to activity concentrations below release levels established by Swedish authorities, were to be transported to Åkers AB, Sweden. At Åkers AB, the ingots were to be remelted in the Åkers commercial foundries, along with uncontaminated scrap, for future use in the manufacture of rolls.
- The radiation doses to workers and other parameters were to be measured (1) during the operations at Studsvik, (2) during transport of the released ingots to Åkers, and (3) during the remelting of the ingots (along with other scrap) and manufacture of rolls from the resulting steel.
- The doses were also to be estimated using the RESRAD-RECYCLE and the CERISE programmes.
- A report was to be prepared comparing the measured radiation doses with those predicted by the calculations.

Participants in the project

The project was a co-operation between the following organisations:

- Swedish Radiation Protection Institute (SSI) initiated the project and is responsible for the central project management and for work not normally within the operational scope of the other partners. SSI constitutes the radiation protection and regulatory authority in Sweden.
- Studsvik RadWaste AB (Sweden) has a facility, in a radiologically controlled area, for melting contaminated metal scrap. The resulting ingots are allowed to decay. Afterwards, the ingots are used as feed material and mixed with uncontaminated scrap by remelting at commercial foundries.
- Åkers AB (Sweden) is a major manufacturer of rolls for both hot and cold rolling in the international steel and non-ferrous metal industries. It is a customer of ingots produced at Studsvik RadWaste AB.
- The United States Department of Energy (USDOE), which has a large number of surplus nuclear facilities, the decommissioning of which will result in a considerable amount of recyclable material. The Department is therefore interested in validating calculation programmes used in connection with the clearance of material from regulatory control.
- Argonne National Laboratory (USA) developed the RESRAD-RECYCLE code under the sponsorship of the United States Department of Energy (USDOE). The code assesses the radiological doses for workers and the public, resulting from exposure to radionuclides in recycled metal with residual radioactivity.
- Institute de Radioprotection et Securité Nucléaire, IRSN, (France) has developed the CERISE code for the dose uptake through different pathways when an individual is exposed to ionising radiation. IRSN is an advisor to the radiation protection authorities in France. The name of IRSN has been changed to Institut de Radioprotection et Securité Nucléaire (IRSN) in Feb 2002.
- Belgoprocess (Belgium) is developing a process of milling very low level contaminated concrete, with a view to recycling it without radiological restrictions. The company is participating as an observer in order to study the possibility of a validation project for the RESRAD-RECYCLE and CERISE codes for concrete.
- Studsvik Stensand AB is a nuclear and other services company within the Studsvik group. Among the services it provides are health physics supervision as well as radiological measurements and analysis.
- Menon Consulting AB, which has been responsible for the project management and co-ordination of the various activities within the project.

Execution of the project

The actual execution of the project was slightly different from that originally planned. The first phase (melting of contaminated scrap at Studsvik, release of ingots and transport to Åkers) was carried out. The ingots were re-melted along with other (uncontaminated) scrap at Åkers to be used for manufacturing rolls. The doses to workers were measured at Studsvik, Åkers and during ingot transport.

Dose calculations were made in parallel with these operations using the RESRAD-RECYCLE and CERISE programmes. However, the results of these calculations could not be compared with the corresponding values of doses taken by workers, because all of the doses were below the limit of detection.

Originally, it was not the aim of the project to make a comparison between the two calculations programmes as such. However, as both programmes were used on the same input basis, it was possible to make certain comparisons.

Due to the fact that there were no detectable doses during the execution of the first phase of the project, it was decided that Phase 2 of the project should involve the melting of scrap with significantly higher levels of activity, instead of being a repetition of Phase 1. This was achieved by studying the melting of a stainless steel fuel rack for the purpose of volume reduction. The activity concentration was about 160 Bq/g, mostly Co-60. The occurrence of detectable doses enabled a comparison between calculated and measured doses.

The fuel rack was melted in the Studsvik facility in the middle of January 2001, in the presence of project team including the dose modellers. Their presence and the discussions that were held in connection with the Phase 2 operation helped to model the calculations in accordance with the operations at Studsvik.

Overview of measurements and calculations during Phase 1

MEASUREMENTS

The measurement campaigns during Phase 1 consisted of:

- background measurements at Åkers. Measurements at Åkers during ‘normal’ melting of scrap (without Studsvik ingots);
- measurements at Åkers during a melt with addition of Studsvik ingots;
- background measurements during transportation between Studsvik and Åkers;
- measurements during transport of ingots from Studsvik to Åkers;
- background measurements at Studsvik new melting facility; and
- dose rate measurements at Studsvik during a complete cycle of melting of radioactive scrap (receipt/segmenting/storage/melting/storage).

The background radiation in the Åkers plant and the scrap yard was 200–300 cps (where 1 cps is approximately equal to 1 nSv/h for Co 60), with a few exceptions where higher levels (700–800 cps) were noted. These slightly elevated areas of activity are probably due to the use of slag from earlier times in building material. No measurable doses over average background (150–200 nSv/h) were observed adjacent to the furnace during the normal melting activities (i.e., without Studsvik ingots). Traces of Ra-226 and Th-232 were found in the slag and dust from furnace ventilation.

During these background measurements, an interesting piece of information was identified: the paint used to coat the moulds for the manufacture of rolls contained 3 500–5 500 Bq/l of Ra-226 (85 %) and Th-232 (15 %). Air sampling revealed no detectable alpha or beta activity. No detectable activity levels were observed during the whole body monitoring of the personnel involved in these operations.

Measurements were also carried out at Åkers during the melting of 24 tons of steel including 7.5 tons of Studsvik ingots with an average activity of 0.4 Bq/g Co-60. The resulting material had an average content of 0.15 Bq/g Co-60.

The on line dose rate measurement adjacent to the furnace showed a slightly higher dose rate: 150–250 nSv/h compared to 150–200 nSv/h during ‘normal’ melting without Studsvik ingots. The background in the rest of the plant was normal, i.e. 200–300 cps. The personal air filter analysis showed the same level of Cs-137 as during normal melting.

During the transport of 30 tons of ingot (average activity concentration 0.4 Bq/g), there was no measurable difference in the dose to the driver, with ingots on the 1.25-hour trip from Studsvik to Åkers or empty on the trip back.

The Studsvik melting facility was brand new, while the cutting hall had been in service for five years, which explains the 300–350 cps background dose rate in the cutting hall, compared to the 200–250 cps in the newer areas. There were considerably higher levels in the neighbourhood of the slag binding product (400 cps), stampmass for the furnace (700 cps), new insulation (600 cps) and the new asphalt outside the plant (700 cps).

On-line dose rate measurements were made in the door between the cutting and melting halls. About seven tons of scrap was melted in three melts during a total of about 8.5 hours. During the first five hours, the dose rate varied between 0.3 and 0.4 µSv/h. During the next three hours, there were two periods of dose rates up to 0.6 µSv/h. There are no direct explanations for this from the melting process point of view.

None of the personnel involved took detectable doses above the limit for registration (i.e. > 0.1 mSv) during the operations.

CALCULATIONS

In the phase I calculations, five scenarios representative of the main working posts in the Studsvik facility were considered. Thirty tons of scrap steel were loaded to the Studsvik induction furnace in 10 three-ton batches and melted. After the melting, the slag material was poured out, cooled, and handled by a slag worker. The steel melt remaining in the furnace was placed in large containers, cooled, and cast into ingots. The solid ingots were subsequently transported to a commercial facility for further processing. Radionuclides considered in dose calculations were Co-60, Zn-65, Sr-90, Tc-99, Cs-137, Am-241, U-238, Pu-239, and Ac-227, each treated separately at an activity concentration of 1 Bq/g.

Dose calculations were conducted for five different activities in the Studsvik facility: (1) sorting and cutting scrap metal after its reception; (2) scrap melting, excluding slag work; (3) slag handling; (4) ingot handling, including transfer and storage of ingot products; and (5) ingot transport. Five scenarios were developed to evaluate the doses to various workers: (1) scrap processor, who sorted and cut scrap metal into smaller pieces for melting, (2) furnace operator, who loaded the scrap metal to the furnace and operated the furnace, (3) slag worker, who removed the slag material from the top of the melt surface with a special tool and put it in a metallic box for cooling, (4) ingot caster, who poured the melt into moulds, moved the moulds for cooling, and removed the solid ingot from the moulds, and (5) ingot truck driver, who transported the solid ingots to Åkers for further processing.

RESRAD-RECYCLE and CERISE used the same mass partitioning factors: 90 % for ingot, 1 % for baghouse dust, and 10 % for slag, for dose calculations. The radionuclide partitioning factors used in dose calculations were different for the two codes.

With one exception, exposure pathways considered for each of the five activities were external radiation, inhalation, and ingestion. For the ingot truck driver, only the external radiation pathway was considered.

To model external radiation exposure, the radiation source was simulated by a full or half cylinder with dimensions (radius and thickness) representing the source geometry. An external dose conversion factor for each scenario was calculated on the basis of the dimensions of the cylindrical source, the exposure distance, and the density of the source material. Attenuation of external radiation was considered for the ingot truck driver scenario, resulting from the shielding of the truck cab.

Best judgement assumptions were made of the inhalation rate and the respirable fraction of the airborne dust. The dust loading factor and concentration of radionuclides in the dust varied according to the source material for the respective operation, e.g. scrap material for scrap processors, slag for slag workers, etc.

Both calculation programmes assumed an incidental ingestion of dust particles, with radionuclide concentrations at the same levels as for inhalation. The RESRAD-RECYCLE calculations assumed, in addition, that inhaled particles larger than of respirable size, would be ingested.

The inhalation and ingestion dose conversion factors used in the RESRAD-RECYCLE calculations were obtained from FGR No. 11 (Eckerman *et al*., 1988). Dose conversion factors used in CERISE calculations were obtained from the EU Basic Safety Standards (Council Directive 96/29/EURATOM). The external dose conversion factors calculated by the two computer codes were obtained by assuming the same geometry and exposure distances; however, the mathematical models used were different.

Because of these differences in the external radiation models of the two calculation codes, the external dose conversion factors are different, generally within a factor of 2 except for the two beta emitters, Sr-90 and Tc-99. The RESRAD-RECYCLE results for those radionuclides are much larger than the CERISE results.

Differences in the external dose results are caused by differences in the external dose conversion factors and differences in the radionuclide partitioning factors. The ratio of the dose results (RESRAD-RECYCLE/CERISE), if adjusted by the ratio of the dose conversion factor and the ratio of the radionuclide partitioning factor, are very close to 1. The only exceptions are the adjusted ratios for Zn-65 for the ingot handling and ingot transport scenarios.

For the inhalation pathway also, there was agreement between the calculation code results, using the same dose conversion and radionuclide partitioning factors, except in the case of Zn-65 for the ingot handling scenario.

The ingestion pathway results show understandable differences due to the RESRAD-RECYCLE assumption of the ingestion of inhaled dust particles larger than of respirable size. If normalised, the RESRAD-RECYCLE/CERISE adjusted ratio is very close to 1 when the inhalation route of exposure is insignificant compared with the incidental ingestion route of exposure (e.g. the reception worker and ingot handling worker scenarios). When the inhalation route of exposure becomes more significant, the value of the adjusted ratio becomes larger. For the melting worker and slag worker, the adjusted ratios are close to 1.5 for all the radionuclides considered. A difference that cannot yet be explained is the small value (about 0.1) of the adjusted ratio for Zn-65 for the ingot handling and ingot transport scenarios.

Overview of execution, measurements and calculation during Phase 2

EXECUTION

The main result of the Phase 1 activities was that the primary aim of the validation exercise, i.e., comparison of actual doses taken by workers with corresponding values calculated by the codes, could not be realised: the doses were, in every case, below the limits of detection. A different approach was therefore used for Phase 2, which had originally been planned to be a repetition of Phase 1. Instead it was decided to melt an object with high enough activity to give detectable doses to workers.

The chosen object was a stainless steel fuel rack from a Swedish nuclear power plant, which had been packed into a 20-foot container. The maximum dose rate on the outside of the container was 0.2 mSv/h. The rack had a total mass of 3.4 (metric) tons. Nuclide specific measurements (made from outside the package) indicated an average radioactivity content of 109 kBq/kg, mostly Co-60. It was expected that such a concentration should give a surface dose of about 50 μSv/h on the ingots after melting. The surface dose rates on the racks before melting would be significantly higher. This implied that the personnel engaged in the various stages of the melting operations would be exposed to measurable doses.

The rack was delivered in the container to Studsvik. Normally, the operations comprising the melting process consist of the following:

- reception of package/unpacking;
- segmenting of racks (plasma torch);
- storage of segmented pieces;
- melting;
- slag handling;
- filter dust handling;
- handling and transport of ingots; and
- storage of ingots.

In the treatment of the fuel rack, the segmented pieces were taken directly for melting, the filter dust quantity was too small to be collected and ‘handled’ and storage of the ingots was not considered.

The truck drivers transported the container with the fuel rack into the melting facility at Studsvik. The scrap unloaders unloaded the fuel rack from the transport vehicle. The scrap cutters/sorters dissembled the fuel rack and cut it into smaller pieces that could be fed to the furnace. The cutting process produced a small quantity of swarf. The furnace operators loaded the fuel rack to the furnace and operated the furnace. After the ingot melt was poured into vertical moulds, the ingot handlers A moved the ingot (in moulds) away for cooling. After cooling, ingot handlers B removed the solid ingots from moulds. The solid ingots were then put on wooden pallets in a storage area by the ingot fork driver. During melting of the fuel rack, slag from the melt surface was removed by the slag handler with a special tool and was put in a metallic box in the same area for further processing.

MEASUREMENTS

All personnel involved in the project operations were equipped with electronic (display) dosimeters. In order to make direct comparisons with the calculations, the electronic dosimeters were provided with dose codes corresponding to various operations, as follows:

Dose code 610: Transport of container into workshop.
Dose code 611: Opening of container, lifting of fuel rack, removing of plastic foil wrapping, setting up rack for cutting.
Dose code 612: Segmenting of fuel rack (plasma torch).
Dose code 613: Melting, slagging, pouring into moulds.
Dose code 614a: Handling of ingots in moulds (i.e. shielded).
Dose code 614b: Handling of ingots after cooling and removal from moulds (i.e. unshielded).
Dose code 615: Transport of ingots to storage.
Dose code 617: Slag handling.

The measurements showed that segmenting was the work operation that gave the highest dose, almost 65 % of the total dose incurred, while melting itself accounted for only about 13 %.

CALCULATIONS

To facilitate dose calculations, the geometry of the radiation source, exposure distance between the source and the worker, and the time span of each operation were developed on the basis of the real operations. All the parameter values used in the dose calculations were based on the Studsvik values except for the inhalation and ingestion dose conversion factors, for which the FGR values and the European Directive values were used by RESRAD-RECYCLE and CE-RISE, respectively.

Eight exposure scenarios were developed to account for the various operations conducted during the melting process. These eight scenarios evaluated doses to the following work groups: (1) scrap truck drivers, (2) scrap unloaders, (3) scrap cutters/sorters, (4) furnace operators, (5) ingot handlers A (during ingot cooling in moulds), (6) ingot handlers B (after ingot cooling and removal from moulds), (7) ingot fork driver, and (8) slag handler.

Mass partitioning factors used in dose calculations were developed from the measured masses of the ingot product, the slag product, and filter dust and with application of the principle of mass conservation. The cutting swarf (2 kg) was neglected in RESRAD-RECYCLE and CE-RISE calculations because its mass was very small compared with the mass of the fuel rack. The partitioning factors used by RESRAD-RECYCLE were 98.35 % for ingot, 1.64 % for slag, and 0.01 % for filter dust. The partitioning factors used by CERISE were 98.3 % for ingot, 1.65 % for slag, and 0.004 % for filter dust.

Radionuclide partitioning factors used for dose calculations were developed on the basis of the measured activity contents in ingot, slag, and dust filters. Like the calculations for mass partitioning factors, for RESRAD-RECYCLE dose calculations, the measured radionuclide contents in the cutting swarf were neglected and subtracted from the total contents. For CERISE dose calculations, the partitioning factors were calculated by normalizing the radionuclide content in ingot, slag, and filter dust, respectively, with the total content of radionuclides (including those in the cutting swarf).

Radionuclide concentrations in the fuel rack were calculated from information on total mass and amount of radionuclides in the three melting products. Concentrations in the fuel rack were calculated as 157 Bq/g for Co-60, 3.66 Bq/g for Sb-125, 0.027 Bq/g for Cs-134, 10.82 Bq/g for Cs-137, and 0.0060 Bq/g for Eu-154.

Exposure pathways considered for dose calculations were external radiation, inhalation, and ingestion. For the ingot handler and ingot fork driver, radiation exposures from the inhalation and ingestion pathways were insignificant because little dust loading occurred during the operations. For the other scenarios, exposures from inhalation and ingestion were considered through the use of an inhalation rate of 1.2 m^3/h and an ingestion rate of 0.00625 g/h.

The source geometries and exposure parameters used by RESRAD-RECYCLE and CERISE for dose calculations were similar for the various operations, except in the case of the ingot handler and ingot fork driver, where different source dimensions were used by the two codes. This difference was due to different perceptions regarding representing a radiation source of five ingots with a cylindrical geometry.

For the scrap truck driver scenario, the external radiation was considered to be attenuated by the truck cab. During the handling of ingot melt, ingot handlers A were shielded from radiation by the moulds, while ingot handlers B were unshielded. The slag container shielded the slag handler. The ingot fork driver took five ingots to storage at a time; therefore, dimensions of the radiation source were developed to consider potential radiation exposure from the five ingots.

The internal dose conversion factors used in RESRAD-RECYCLE calculations were obtained from FGR 11; those used in CERISE calculations were obtained from European Directive. Dose conversion factors for external radiation were calculated by the two codes.

Among the three exposure pathways analysed, radiation exposure from the external radiation pathway was far more significant than radiation exposure from the two internal radiation pathways (inhalation and ingestion). Radiation exposures incurred by the scrap unloaders and scrap cutters/sorters were greater than those incurred by the other workers because of the closer exposure distances and longer exposure times experienced by the scrap unloaders and scrap cutters/sorters.

External radiation doses calculated by RESRAD-RECYCLE were smaller than those calculated by CERISE for the scrap truck drivers, scrap unloader, and scrap cutter/sorter. For the furnace operator and ingot handler scenarios, in contrast, RESRAD-RECYCLE results were greater than CERISE results. For the ingot fork driver and slag handler, dose results from the two codes were about the same. Larger differences were observed for the two ingot handling scenarios because of different geometries and dimensions assumed in the dose calculations.

Comparison of calculations with measurements/conclusions

Table I shows a comparison of the RESRAD-RECYCLE and CERISE calculation results with the electronic dosimeter measurements for each dose code. The table has been divided into doses taken during work preparatory to melting and doses taken during and after melting.

Some comments on the table:

- Significant measured doses are noted only for the following scenarios: unloading of the fuel rack (611) and its cutting (612) and for the melting operations (613). For the other scenarios, measured doses are given but these are very low due to the short duration of work station activity (fuel rack transport into the building, ingot and slag handling, ingot truck transport).
- The part sum of doses shows that the pre-melting preparatory work accounted for 84 % of the total doses, while the melting itself with ingot and slag handling were responsible for the remaining 16 %.
- There is an overestimation by the codes for the doses under dose codes 611, 612 and 614b, covering 86 % of the total dose; and an underestimation of the doses under codes 613 and 617.

Table I. *Phase 2 – Comparison of doses per dose code between RESRAD-RECYCLE/CERISE and electronic dosimeter measurements. (All values in micromanSv.)*

				Measurements			Ratios to measurements (excl. background)	
Code		**RESRAD-RECYCLE**	**CERISE**	**Incl. back-ground**	**Excl. back-ground**	**Background**	**RESRAD-RECYCLE**	**CERISE**
610	Transport of container into workshop	2.5	4	1	< 1			–
611	Opening of container	156	256	43	38	5.2	4.1	6.7
612	Segmenting	536	812	121	107	13.9	5.0	7.6
Part sum regarding work preparatory to melting		694.5	1 072	165	145		4.2	7.4
613	Melting (with shielding)	4	1.7	32	22	10.1	0.18	0.08
614a	Handling of ingots in moulds	0.1	0.02	1	< 1	0.1		–
614b	Handling of ingots after removal from moulds	22	4.3	4	4	< 0.1	5.5	1.1
615	Transport of ingots to storage	0.1	0.1			<0.1		–
617	Slag handling	1.3	1.3	2	1.8	0.2	0.7	0.7
Total		722	1 080	204	173		4.2	6.2

The comparison of the calculation results indicates that, even with a carefully controlled reflection of reality with respect to geometry and exposure time and with a 'best judgement' choice of densities for each operation, the calculation programmes have tended to overestimate the measured values of the total dose by a factor 4 to 6, i.e. about an order of magnitude. An obvious explanation is the fact that the workers are not static, they move about constantly, changing the geometry, thus not taking the assumed doses.

Other practical aspects difficult to reflect exactly in the calculations are:

- modelling of the source geometry (during cutting);
- estimation of the density (during cutting);
- estimation of the mean distance to the source (during cutting and melting);
- dimensions of the source (during cutting and melting); and
- estimation of shielding thickness (during melting).

The codes assume a source with mass specific distribution of radioactivity (Bq/g), while, in most cases, the actual object has the corresponding total activity concentrated on its surface. This should lead to an underestimation of the dose uptake by the workers involved in segmenting. However, the conservatism of the above listed factors obviously more than compensates for this, as is shown by the overestimation of the doses in total by the codes.

It seems reasonable to state that the use of 'enveloping' scenarios, which necessarily cover a wide range of scenarios in connection with the calculation of clearance levels, would tend to accentuate this tendency of overestimation of dose uptake in most individual cases of recycling by melting. Taking into account the sensitivity of the modelling and the practical aspects listed above, the estimated doses can be, say, one or even more orders of magnitude higher than those actually taken.

It should be pointed out that the Phase 2 melting was performed on a typical reactor system component with only gamma emitters, with Co-60 and Cs-137 as the dominant radionuclides. The dose incurred was almost exclusively by external exposure. This is in agreement with the dose modelling results.

A side aspect of the execution of the Validation Project – specifically the background measurements – was the revelation of radioactivity in unexpected places: the paint used for the painting of moulds at Åkers (3-5 Bq/g), the slag binding product (twice background radiation), the stamp mass, insulation and new asphalt at the Studsvik furnace (all at three to four times background). This serves to illustrate the undetected omnipresence of radioactivity in the human habitat at dose rate levels considerably higher (up to 400 % over background) than the levels (ca 1 % over background) at which the currently proposed clearance criteria are based on.

Finally, it is important to note that the degree of overestimation (a factor of 4-6), as recorded in the validation project, is generally regarded as 'acceptable' by dose modellers. The results will most probably not lead to any revision or refinement of these codes. For the nuclear decommissioner and the other producers of large volumes of only slightly radioactively contaminated material, the clearance levels resulting from such a degree of conservatism can lead to huge amounts of material unnecessarily being condemned to burial as radioactive waste. Considering that most such producers transfer their costs to the public, it is society at large that will foot the bill for this exercise in conservatism.

1 Introduction

For the nuclear industry, the minimisation of the volumes of radioactive waste arising from the refurbishment or decommissioning of nuclear facilities, has been a high priority goal. The recycling of very low level radioactive material (or its reuse or disposal) without radiological restrictions, instead of disposal as radioactive waste, has long been identified as a significant means of achieving this aim. It is from the health and environmental protection perspective imperative that such recycling (or similar) is guided by reasonable and internationally harmonised regulations that restrict or minimise radiological consequences. However, the absence of consistent, internationally accepted criteria to regulate the release of recyclable material from regulatory control significantly restricts the utilisation of recycling and reuse as material management practices.

Regulations, interim proposals or recommendations are in existence for the 'clearance' of material from regulatory control, such as those from the US Nuclear Regulatory Commission, the International Atomic Energy Agency, the European Commission and other agencies. All proposals are based on predicted scenarios for subsequent utilisation of the released materials. The calculation models used in these scenarios tend to utilise conservative data regarding exposure times and dose uptake as well as other assumptions as a safeguard against uncertainties. This conservatism due to uncertainties is also apparent in similar work performed by the Task Group on Recycling and Reuse of the OECD/NEA Co-operative Programme on Decommissioning and also in the USNRC's NUREG/CR-5512: Technical Basis for Converting Contamination Levels to Annual Total Effective Dose Equivalent.

Another aspect is common to all these calculation models and codes: none of them has ever been validated by comparison with the actual real life practice of recycling. The Swedish Radiation Protection Institute initiated the Validation Project in order to validate some of the assumptions made in these calculation models, and thereby better assess the radiological consequences of recycling on a practical large scale.

2 Overview of the validation project

2.1 Aim of the project

The purpose of the validation project was to register the radiation dose to workers and the public exposed to a certain chain of exposures and to compare the registered doses with the results of computer programme calculations for the same chain of exposures. The following process of management of radioactively contaminated material was chosen to serve as model for comparison:

- melting of contaminated scrap at a radiologically controlled facility.
- release of ingots from regulatory control with a known activity concentration level, for remelting (with uncontaminated scrap) at a commercial melter.
- use of the resulting material in the manufacture of industrial products.
- the radiological parameters and consequences (i.e. activity concentrations, dose rates, doses, etc.) of each of the above operations were to be measured by suitable and available means.
- the measurements were to be compared with the results of calculations by computer programmes currently used by various organisations.

Specifically:

- Two consignments of contaminated scrap, each of about 30 tons, were to be melted at Studsvik RadWaste, Sweden.
- Ingots resulting from this melting, which have decayed to activity concentrations below release levels established by Swedish authorities, were to be transported to Åkers AB, Sweden. At Åkers AB, the ingots were remelted in the Åkers commercial foundries, along with uncontaminated scrap, for future use in the manufacture of rolls.
- The radiation doses to workers and other parameters were to be measured (1) during the operations at Studsvik, (2) during transport of the released ingots to Åkers, and (3) during the remelting of the ingots (along with other scrap) and manufacture of rolls from the resulting steel.
- The doses were also to be estimated using the RESRAD-RECYCLE and the CERISE programmes.
- A report was to be prepared comparing the measured radiation dose with those predicted by the calculations.

2.2 Participants in the project

The project was a co-operation between the following organisations:

- Swedish Radiation Protection Institute (SSI) initiated the project and is responsible for the central project management and for work not normally within the operational scope of the other partners. SSI constitutes the radiation protection and regulatory authority in Sweden.
- Studsvik RadWaste AB (Sweden) has a facility, in a radiologically controlled area, for melting contaminated metal scrap. The resulting ingots are allowed to decay. Afterwards, the in-

gots are used as feed material and mixed with uncontaminated scrap for remelting at commercial foundries.

- Åkers AB (Sweden) is a major manufacturer of rolls for both hot and cold rolling in the international steel and non-ferrous metal industries. It is a customer of ingots produced at Studsvik RadWaste AB.
- The United States Department of Energy (USDOE), which has a large number of surplus nuclear facilities, the decommissioning of which will result in a considerable amount of recyclable material. The Department is therefore interested in validating calculation programmes used in connection with the clearance of material from regulatory control.
- Argonne National Laboratory (USA) developed the RESRAD-RECYCLE code under the sponsorship of the United States Department of Energy (USDOE). The code assesses the radiological doses for workers and the public, resulting from exposure to radionuclides in recycled metal with residual radioactivity.
- Institut de Radioprotection et Securité Nucléaire (IRSN) (formerly Institute de Protection et Securité Nucléaire, IPSN), (France) has developed the CERISE code for the dose uptake through different pathways when an individual is exposed to ionising radiation. IRSN is an advisor to the radiation protection authorities in France.
- Belgoprocess (Belgium) is developing a process of milling very low level contaminated concrete, with a view to recycling it without radiological restrictions. The company is participating as an observer in order to study the possibility of a validation project for the RESRAD-RECYCLE and CERISE codes for concrete.
- Studsvik Stensand is a nuclear and other services company within the Studsvik group. Among the services it provides are health physics supervision as well as radiological measurements and analysis.
- Menon Consulting AB, which has been responsible for the project management and coordination of the various activities within the project.

The complete list of participants in the project team is given in Attachment 1. More details of the participating organisations, the contractors and their activities and programmes are given in Attachment 2.

2.3 Execution of the project

The actual execution of the project was slightly different from that originally planned. The first phase (melting of contaminated scrap at Studsvik, release of ingots and transport to Åkers) was carried out. The ingots were re-melted along with other (uncontaminated) scrap at Åkers to be used for manufacturing rolls. The doses to workers were measured at Studsvik, Åkers and during ingot transport.

Dose calculations were made in parallel with these operations using the RESRAD-RECYCLE and CERISE programmes. However, the results of these calculations could not be compared with the corresponding values of doses taken by workers, because all of the doses were below the limit of detection. As there was no comparison possible, the direct results of the calculations on the Åkers operations are not reported. However, certain default parameter code calculations were made, as described below.

Originally, it was not the aim of the project to make a comparison between the two calculations programmes as such. However, as both programmes were used on the same input basis (default parameters), it was possible to make certain comparisons. The results of these comparisons are shown in Attachment 8.

Due to the fact that there were no detectable doses during the execution of the first phase of the project, it was decided that Phase 2 of the project should involve the melting of scrap with significantly higher levels of activity, instead of being a repetition of Phase 1. Then the occurrence of detectable doses would make a comparison possible between calculated and measured doses. The object chosen for melting during Phase 2 was a stainless steel fuel rack with an estimated activity concentration of over 100 Bq/g, mostly Co-60.

The fuel rack was melted in the Studsvik facility in the middle of January 2001, in the presence of project team including the dose modellers. Their presence and the discussions that were held in connection with the Phase 2 operation helped to model the calculations in accordance with the operations at Studsvik.

3 Phase 1 activities

Activities during Phase 1 consisted of a number of measurements and calculations.

3.1 Measurements

The measurement campaigns consisted of:

- background measurements at Åkers. Measurements at Åkers during 'normal' melting of scrap (without Studsvik ingots);
- measurements at Åkers during a melt with addition of Studsvik ingots;
- background measurements during transportation between Studsvik and Åkers;
- measurements during transport of ingots from Studsvik to Åkers;
- background measurements at Studsvik new melting facility;
- dose rate measurements at Studsvik during a complete cycle of melting of radioactive scrap (receipt/segmenting/storage/melting/storage).

Details of these campaigns are given in Attachment 3. Below are some overview results and comments to the measurement campaigns.

3.1.1 BACKGROUND MEASUREMENTS AT ÅKERS

The radiation measurements were carried out with fifteen area TLD dosimeters, two workers with TLD dosimeters, an FHT 3 M instrument (where 1 cps is approximately equal to 1 nSv/h for Co-60) and a low dose rate measuring instrument with continuous (3 minute intervals) registration (ESM FH 40G-10). Two workers were fitted with air sampling masks.

The background radiation in the plant and the scrap yard was 200–300 cps, with a few exceptions where higher levels (700–800 cps) were noted. These slightly elevated areas of activity are probably due to the use of slag from earlier times in building material. No measurable doses were registered in the TLDs and no peak values over average background (150–200 nSv/h) were observed adjacent to the furnace during the normal melting activities (i.e., without Studsvik ingots). Fifteen samples were taken for radiochemical measurements. Traces of Ra-226 and Th-232 were found in the slag and dust from furnace ventilation.

During these background measurements, an interesting piece of information was identified: the paint used to coat the moulds for the manufacture of rolls contained 3 500–5 500 Bq/l of Ra-226 (85 %) and Th-232 (15 %). Air sampling revealed no detectable alpha or beta activity. No detectable activity levels were observed during the whole body monitoring of the personnel involved in these operations.

3.1.2 MEASUREMENT AT ÅKERS WITH ADDITION OF STUDSVIK INGOTS

These measurements were carried out during the melting of 24 tons of steel including 7.5 tons of Studsvik ingots with an average activity of 0.4 Bq/g Co-60. The resulting material had an average content of 0.15 Bq/g Co-60.

The measurement instrumentation and sampling was as described in Section 3.1.1. The melted material was cut into blocks for storage in large boxes for continued manufacturing operations (casting of rolls, machining, surface treatment, etc.) at a later date.

The on line dose rate measurement adjacent to the furnace showed a slightly higher dose rate: 150–250 nSv/h compared to 150–200 nSv/h during ‘normal’ melting without Studsvik ingots. The background in the rest of the plant was the same as in Section 3.1.1, i.e. 200–300 cps. The personal air filter analysis showed the same level of Cs-137 as during normal melting.

3.1.3 MEASUREMENT OF DOSE RATE DURING TRANSPORT OF INGOTS

The dose rate in the cab of the truck was registered with an on line FH 40G-10 instrument, during the transport of 30 tons of ingot (average activity concentration 0.4 Bq/g). There was no measurable difference in the dose to the driver, with ingots on the 1.25-hour trip from Studsvik to Åkers or empty on the trip back.

3.1.4 BACKGROUND MEASUREMENTS/MEASUREMENTS DURING MELTING AT STUDSVIK

Measurements during melting at Studsvik are shown in detail in Section 4 of Attachment 3. The following is a brief summary of these measurements and their results:

The melting facility was brand new, while the cutting hall had been in service for five years, which explains the 300–350 cps background dose rate in the cutting hall, compared to the 200–250 cps in the newer areas. There were considerably higher levels in the neighbourhood of the slag binding product (400 cps), stampmass for the furnace (700 cps), new insulation (600 cps) and the new asphalt outside the plant (700 cps).

The on-line dose rate measurements in the door between the cutting and melting halls are shown in Section 4.2 of Attachment 1. About seven tons of scrap was melted in three melts during a total of about 8.5 hours. During the first five hours, the dose rate varied between 0.3 and 0.4 µSv/h. During the next three hours, there were two periods of dose rates up to 0.6 µSv/h. There are no direct explanations for this from the melting process point of view.

The loose contamination on the scrap items was determined by smear tests. All samples except one showed no detectable loose contamination. The exception showed a level of 15.6 kBq/m^2 of Co-60. The 140 kg of slag produced had a total activity of 455 kBq (mainly Cs-137).

None of the personnel involved took detectable doses above the limit (i.e. > 0.1 mSv) for registration during the operations.

3.2 Calculations

In the phase I calculations, five scenarios representative of the main working posts in the Studsvik facility were considered. Thirty tons of scrap steel were loaded to the Studsvik induction furnace in 10 three-ton batches and melted. After the melting, the slag material was poured out, cooled, and handled by a slag worker. The steel melt remaining in the furnace was placed in large containers, cooled, and cast into ingots. The solid ingots were subsequently transported to a commercial facility for further processing. Radionuclides considered in dose calculations were Co-60, Zn-65, Sr-90, Tc-99, Cs-137, Am-241, U-238, Pu-239, and Ac-227.

The exposure parameters and source dimensions used in dose calculations were derived from the RESRAD-RECYCLE default values, which were modified to accommodate the smaller throughput and smaller furnace capacity. For dose calculations, RESRAD-RECYCLE and CERISE used their own dose conversion factors and partitioning factors.

Because of the low level of contamination in the scrap metal, radiation exposures measured in the melting facility could not be differentiated from background level. Therefore, no measurement data were available to validate the calculation results obtained with the models. This phase I exercise was essentially a benchmarking calculation, rather than a validation calculation. However, the calculation results of both RESRAD-RECYCLE and CERISE codes confirmed that radiation doses resulting from processing the contaminated scrap steel are low (less than 10^{-6} Sv).

3.2.1 SCENARIO DESCRIPTION

Dose calculations were conducted for five different activities in the Studsvik facility: (1) sorting and cutting scrap metal after its reception; (2) scrap melting, excluding slag work; (3) slag handling; (4) ingot handling, including transfer and storage of ingot products; and (5) ingot transport. Five scenarios were developed to evaluate the doses to various workers: (1) scrap processor, who sorted and cut scrap metal into smaller pieces for melting, (2) furnace operator, who loaded the scrap metal to the furnace and operated the furnace, (3) slag worker, who removed the slag material from the top of the melt surface with a special tool and put it in a metallic box for cooling, (4) ingot caster, who poured the melt into moulds, moved the moulds for cooling, and removed the solid ingot from the moulds, and (5) ingot truck driver, who transported the solid ingots to Åkers for further processing.

3.2.2 MASS PARTITIONING FACTORS

RESRAD-RECYCLE and CERISE used the same mass partitioning factors: 90 % for ingot, 1 % for baghouse dust, and 10 % for slag, for dose calculations

3.2.3 RADIONUCLIDE PARTITIONING FACTORS

The radionuclide partitioning factors used in dose calculations were different for the two codes. The values used are listed in Table 1 for comparison.

3.2.4 EXPOSURE PATHWAYS

With one exception, exposure pathways considered for each of the five activities were external radiation, inhalation, and ingestion. For the ingot truck driver, only the external radiation pathway was considered.

To model external radiation exposure, the radiation source was simulated by a full or half cylinder with dimensions (radius and thickness) representing the source geometry. An external dose conversion factor for each scenario on the basis of the dimensions of the cylindrical source, the exposure distance, and the density of the source material was then calculated. Attenuation of external radiation was considered for the ingot truck driver scenario, resulting from the shielding of the truck cab which was assumed to have a density of 7.86 g/cm^3 and a thickness of 0.5 cm.

The inhalation pathway considers radiation exposures resulting from inhalation of airborne dust particles. An inhalation rate of 1.2 m^3/h and a respirable fraction of 0.1 were assumed in dose calculations. The dust loading factor, which is the concentration of airborne dust particles and represents the air quality in the work place, was assumed to be 1 x 10^{-4} g/m^3 for the scrap processor and ingot handler scenarios and 3 x 10^{-3} g/m^3 for the furnace operator and slag worker scenarios. Concentrations of radionuclides in the airborne dust particles were assumed to be the same as those in the source material except for the furnace operator scenario. For the scrap processor scenario, the source material was the scrap metal. For the slag worker scenario, the source material was the slag. For the ingot handler scenario, the source material was the ingot. For the furnace operator scenario, dust particles in the air were considered to originate from the melt mixture inside the furnace. However, only volatile components of the mixture would become airborne, and a fraction of them would eventually be collected in the baghouse. Therefore, concentrations of radionuclides in the airborne dust particles were assumed to be the same as those collected by the baghouse filter.

For the ingestion pathway, it was assumed that the worker would incidentally ingest the dust particles that deposit on his hands or on the surface of surrounding materials with which his hands came in contact. An ingestion rate of 0.00625 g/h was assumed for the dose calculations. The concentrations of radionuclides in the dust particles were assumed to be the same as those used for the inhalation pathway. In addition to incidental ingestion, RESRAD-RECYCLE considered another exposure route through the inhalation pathway. RESRAD-RECYCLE assumed that dust particles larger than the respirable size would enter the gastrointestinal tract after they were inhaled. Once these particles were absorbed into the blood stream, they would result in internal radiation exposure, and the resulting radiation doses were attributed to the ingestion pathway.

3.2.5 SOURCE GEOMETRIES AND EXPOSURE PARAMETERS

Source geometries and exposure parameters used in dose calculations are listed in Table 2. Depending on the scenario, the source geometry was represented by either a full or a half cylinder. The corresponding radius and thickness, together with the assumed density, gives the mass of the radiation source.

Table 2 also lists the dust loading factors, which represent the air quality in the work place, the exposure duration, and the number of workers required for each activity.

3.2.6 DOSE CONVERSION FACTORS

The inhalation and ingestion dose conversion factors used in the RESRAD-RECYCLE calculations were obtained from FGR No. 11 (Eckerman *et al.*, 1988). Dose conversion factors used in CERISE calculations were obtained from the EU Basic Safety Standards (Council Directive 96/29/EURATOM). They are listed in Table 3 for comparison.

Table 4 compares the external dose conversion factors calculated by the two computer codes. The dose conversion factors were obtained by assuming the same geometry and exposure distances; however, the mathematical models used were different.

3.2.7 RESULTS AND COMPARISONS

Differences in external dose conversion factors (shown in Table 3) were expected because the external radiation models used in RESRAD-RECYCLE and CERISE are different. In general, the differences are within a factor of 2 except for the two beta emitters, Sr-90 and Tc-99. The RESRAD-RECYCLE results for those radionuclides are much larger than the CERISE results.

Differences in the external dose results (shown in Tables 5–9) are caused by differences in the external dose conversion factors and differences in the radionuclide partitioning factors. The ratio of the dose results (RESRAD-RECYCLE/CERISE), if adjusted by the ratio of the dose conversion factor and the ratio of the radionuclide partitioning factor, should be very close to 1. This expectation is, for the most part, verified by the values listed under the column ‘Adjusted

Ratio' for external radiation in the tables. The only exceptions are the adjusted ratios for Zn-65 for the ingot handling and ingot transport scenarios.

CERISE was able to reproduce RESRAD-RECYCLE results for the inhalation pathway, if RESRAD-RECYCLE's values for the exposure parameters, the dose conversion factors, and the radionuclide partitioning factors were used in the CERISE calculations. This is verified by the values listed under 'Adjusted Ratio' column for the inhalation pathway in Tables 5–9. All the listed values are very close to 1 except for Zn-65 for the ingot handling scenario.

For the ingestion pathway, the major difference between RESRAD-RECYCLE and CERISE results was the inhalation route of exposure considered in RESRAD-RECYCLE. RESRAD-RECYCLE includes exposure resulting from the inhalation of dust particles larger than the respirable size. Because of this additional route of exposure, ingestion radiation doses calculated by RESRAD-RECYCLE would be greater than those calculated by CERISE under the same exposure conditions. This situation is observed in the results listed under the 'Adjusted Ratio' column for ingestion in Tables 5–9. The adjusted ratio is very close to 1 when the inhalation route of exposure is insignificant compared with the incidental ingestion route of exposure. This condition is shown by the reception worker and ingot handling worker scenarios. The dust loading factor specified in dose calculations was 1.0 x 10^{-4} g/m^3 for these two scenarios. When the inhalation route of exposure becomes more significant, the value of the adjusted ratio becomes larger. For the melting worker and slag worker, the adjusted ratios are close to 1.5 for all the radionuclides considered. The dust loading factor used in dose calculation was 3.0 x 10^{-3} g/m^3 for both scenarios. A difference that cannot yet be explained is the small value (about 0.1) of the adjusted ratio for Zn-65 for the ingot handling and ingot transport scenarios.

Table 1. *Radionuclide partitioning factors used in Phase I RESRAD-RECYCLE and CERISE calculations.*

Radio-nuclides	Ingot (%)		Baghouse (%)		Slag (%)		Total (%)	
	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Ac-227	0	10	1	0.5	99	100	100	110.5
Am-241	0	10	1	0.1	99	100	100	110.1
Co-60	99	100	1	0.5	0	1	100	101.5
Cs-137	0	0.1	97	100	3	10	100	110.1
Pu-239	0	10	1	0.1	99	100	100	110.1
Sr-90	0	10	1	10	99	100	100	120
Tc-99	99	10	1	0.1	0	100	100	110.1
U-238	0	10	1	0.1	99	100	100	110.1
Zn-65	1	1	99	100	0	1	100	102

***Table 2.** Source geometry and exposure parameters used in Phase I dose calculations.*

Studsvik scenario	RESRAD-RECYCLE Scenario	Source Geometry	Mass (t)	Density (g/cm^3)	Thickness (cm)	Radius (cm)	Distance (cm)	Time (h)	Source material [a)] for the external pathway	Source material [a)] for the internal pathways	Dust loading (g/m^3)	Number of workers
Reception sorting/cutting	Scrap processor	1 half cylinder	3	5.90	60	73	30	5	Scrap	Scrap	1E-4	2
Melting (excl. slag work)	Furnace operator	1 full cylinder	3	7.86	76	40	60	3	Scrap	Baghouse filter	3E-3	2
Slag worker	Slag worker	1 half cylinder	0.3	2.70	30	48	75	0.2	Slag	Slag	3E-3	1
Ingot handling (transfer/storage)	Ingot caster	1 half cylinder	2.7	7.86	81	52	60	0.2	Ingot	Ingot	1E-4	1
Transport	Ingot truck driver [b)]	1 full cylinder	7.5	7.86	121	50	200	2	Ingot	None	0	1

[a] Radionuclide concentrations in the specified materials were used in the pathway calculations for the various steps of the process.
[b] A steel shielding material with a density of 7.86 g/cm^3 and a thickness of 0.5 cm was assumed to be present for external dose calculations.

***Table 3.** Internal dose conversion factors used in RESRAD-RECYCLE and CERISE calculation.*

	Inhalation (Sv/Bq)		Ingestion (Sv/Bq)	
Radionuclides	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Ac-227	4.00E-6	1.21E-6	1.82E-3	5.67E-4
Am-241	9.84E-7	2.00E-7	1.20E-4	4.20E-5
Co-60	7.28E-9	3.40E-9	5.91E-8	1.00E-8
Cs-137	1.35E-8	1.30E-8	8.63E-9	4.60E-9
Pu-239	9.56E-7	2.50E-7	1.16E-4	5.00E-5
Sr-90	4.13E-8	3.07E-8	3.54E-7	3.74E-8
Tc-99	3.95E-10	6.40E-10	2.25E-9	4.00E-9
U-238	7.27E-8	4.89E-8	3.20E-5	2.91E-6
Zn-65	3.90E-9	3.90E-9	5.50E-9	1.60E-9

Table 4. *External dose conversion factors calculated for the Phase I scenarios* [a)].

Radionuclide	External dose conversion factors [(Sv/h)/(Bq/g)]									
	Reception		Melting		Ingot handling		Slag worker		Ingot transport	
	RESRAD-RECYCLE	CERISE [b)]	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE [b)]	RESRAD-RECYCLE	CERISE [b)]	RESRAD-RECYCLE	CERISE
Co-60	1.48E-07	1.14E-07	7.66E-08	6.17E-08	5.66E-08	4.49E-08	3.34E-08	2.86E-08	1.37E-08	1.10E-08
Zn-65	3.40E-08	2.56E-08	1.77E-08	1.38E-08	1.30E-08	1.01E-08	7.70E-09	6.45E-09	3.10E-09	2.46E-09
Sr-90	3.79E-11	1.95E-16	1.99E-11	1.05E-16	1.44E-11	7.65E-17	9.07E-12	4.95E-17	0.00E+00	1.87E-17
Tc-99	1.87E-13	3.73E-15	1.01E-13	2.02E-15	7.34E-14	1.47E-15	4.66E-14	9.45E-16	3.93E-15	3.59E-16
Cs-137	3.14E-08	2.11E-08	1.64E-08	1.14E-08	1.21E-08	8.30E-09	7.15E-09	5.35E-09	2.75E-09	2.03E-09
Am-241	3.98E-11	6.45E-11	2.14E-11	3.51E-11	1.56E-11	2.55E-11	1.00E-11	1.65E-11	3.15E-14	6.24E-12
U-238	9.89E-10	7.55E-10	5.16E-10	4.10E-10	3.80E-10	2.99E-10	2.24E-10	1.91E-10	8.63E-11	7.29E-11
Pu-239	1.21E-12	7.75E-13	6.41E-13	4.21E-13	4.68E-13	3.07E-13	2.90E-13	1.98E-13	7.45E-14	7.49E-14
Ac-227	1.40E-08	9.05-09	7.38E-09	4.91E-09	5.41E-09	3.58E-09	3.27E-09	2.31E-09	1.11E-09	8.74E-10

a) Shading identifies areas of larger differences between the results of the two models.
b) The original CERISE values were for a full cylinder source. They were divided by 2 to give values for a half-cylinder source, which was assumed for the scenario.

Table 5. Phase I dose calculation results for the reception worker scenario [a)].

Radionuclide	External radiation (Sv)				Inhalation (Sv)				Ingestion (Sv)			
	RESRAD-RECYCLE	CERISE	RESRAD/ CERISE [b)]	Adjusted ratio [c)]	RESRAD-RECYCLE	CERISE	RESRAD/ CERISE [b)]	Adjusted ratio [c)]	RESRAD-RECYCLE	CERISE	RESRAD/ CERISE [b)]	Adjusted ratio [c)]
Co-60	6.92E-07	5.34E-07	1.30E+00	1	3.32E-12	5.62E-13	5.91E+00	1	2.17E-10	9.96E-11	2.18E+00	1.02
Zn-65	1.06E-07	7.96E-08	1.33E+00	1	2.06E-13	5.98E-14	3.44E+00	1	7.72E-11	7.58E-11	1.02E+00	1.02
Sr-90	1.87E-10	9.60E-16	1.95E+05	1	2.10E-11	2.22E-12	9.46E+00	1	1.30E-09	9.48E-10	1.37E+00	1.02
Tc-99	9.34E-13	1.86E-14	5.02E+01	1	1.35E-13	2.40E-13	5.63E-01	1	1.26E-11	2.00E-11	6.30E-01	1.02
Cs-137	1.55E-07	1.04E-07	1.49E+00	1	5.12E-13	2.72E-13	1.88E+00	1	4.24E-10	4.02E-10	1.05E+00	1.02
Am-241	1.99E-10	3.24E-10	6.14E-01	1	7.19E-09	2.52E-09	2.85E+00	1	3.13E-08	6.26E-09	5.00E+00	1.02
U-238	4.94E-09	3.78E-09	1.31E+00	1	1.92E-09	1.74E-10	1.10E+01	1	2.31E-09	1.53E-09	1.51E+00	1.02
Pu-239	6.03E-12	3.88E-12	1.55E+00	1	6.96E-09	3.00E-09	2.32E+00	1	3.04E-08	7.82E-09	3.89E+00	1.02
Ac-227	6.87E-08	4.46E-08	1.54E+00	1	1.07E-07	3.36E-08	3.18E+00	0.99	1.25E-07	3.72E-08	3.36E+00	1.02

[a)] Shading identifies areas of larger differences between the results of the two models.

[b)] RESRAD/CERISE: Ratio of RESRAD-RECYCLE results to CERISE results.

[c)] Adjusted Ratio: The calculated ratio of RESRAD-RECYCLE results to CERISE results if the same dose conversion factor and radionuclide partitioning factor were used in dose calculation. Calculated by adjusting the RESRAD/CERISE ratio with the corresponding ratio of dose conversion factor and radionuclide partitioning factor.

Table 6. *Phase I dose calculation results for the melting worker scenario [a)].*

Radionuclide	External radiation (Sv)				Inhalation (Sv)				Ingestion (Sv)			
	RESRAD-RECYCLE	CERISE	RESRAD/CERISE [b)]	Adjusted ratio [c)]	RESRAD-RECYCLE	CERISE	RESRAD/CERISE [b)]	Adjusted ratio [c)]	RESRAD-RECYCLE	CERISE	RESRAD/CERISE [b)]	Adjusted ratio [c)]
Co-60	2.15E-07	1.73E-07	1.24E+00	1	5.98E-11	5.06E-12	1.18E+01	1	1.94E-10	2.98E-11	6.51E+00	1.52
Zn-65	3.30E-08	2.58E-08	1.28E+00	1	3.76E-10	1.08E-10	3.48E+00	1.02	6.84E-09	4.54E-09	1.51E+00	1.52
Sr-90	5.89E-11	3.12E-16	1.89E+05	1	3.78E-10	3.98E-10	9.50E-01	1	1.16E-09	5.68E-09	2.04E-01	1.52
Tc-99	3.02E-13	6.06E-15	4.98E+01	1	2.43E-12	4.32E-13	5.63E+00	1	1.12E-11	1.20E-12	9.33E+00	1.51
Cs-137	4.87E-08	3.38E-08	1.44E+00	1	8.94E-10	4.92E-10	1.82E+00	1	3.69E-08	2.40E-08	1.54E+00	1.53
Am-241	6.43E-11	1.05E-10	6.12E-01	1	1.29E-07	4.54E-09	2.84E+01	0.99	2.80E-08	3.74E-10	7.49E+01	1.52
U-238	1.55E-09	1.23E-09	1.26E+00	1	3.46E-08	3.14E-10	1.10E+02	1	2.07E-09	9.16E-11	2.26E+01	1.52
Pu-239	1.92E-12	1.26E-12	1.52E+00	1	1.25E-07	5.40E-09	2.31E+01	1	2.72E-08	4.68E-10	5.81E+01	1.52
Ac-227	2.18E-08	1.45E-08	1.50E+00	1	1.93E-06	3.02E-07	6.39E+00	1	1.12E-07	1.12E-08	1.00E+01	1.51

[a)] Shading identifies areas of larger differences between the results of the two models.

[b)] RESRAD/CERISE: Ratio of RESRAD-RECYCLE results to CERISE results.

[c)] Adjusted Ratio: The calculated ratio of RESRAD-RECYCLE results to CERISE results if the same dose conversion factor and radionuclide partitioning factor were used in dose calculation. Calculated by adjusting the RESRAD/CERISE ratio with the corresponding ratio of dose conversion factor and radionuclide partitioning factor.

Table 7. *Phase I dose calculation results for the slag worker scenario [a)].*

Radionuclide	External radiation (Sv)				Inhalation (Sv)				Ingestion (Sv)			
	RESRAD-RECYCLE	CERISE	RESRAD/CERISE [b)]	Adjusted ratio [c)]	RESRAD-RECYCLE	CERISE	RESRAD/CERISE [b)]	Adjusted ratio [c)]	RESRAD-RECYCLE	CERISE	RESRAD/CERISE [b)]	Adjusted ratio [c)]
Co-60	0.00E+00	5.37E-10	0.00E+00	0.00E+00	0.00E+00	6.78E-14	0.00E+00	0.00E+00	0.00E+00	3.99E-13	0.00E+00	0.00E+00
Zn-65	0.00E+00	8.04E-10	0.00E+00	0.00E+00	0.00E+00	7.20E-14	0.00E+00	0.00E+00	0.00E+00	3.03E-12	0.00E+00	0.00E+00
Sr-90	1.77E-11	9.81E-17	1.80E+05	0.99	2.49E-10	2.67E-11	9.33E+00	1	7.67E-10	3.81E-10	2.01E+00	1.51
Tc-99	0.00E+00	1.91E-15	0.00E+00	0.00E+00	0.00E+00	2.90E-12	0.00E+00	0.00E+00	0.00E+00	8.01E-12	0.00E+00	0.00E+00
Cs-137	4.24E-10	1.06E-09	4.00E-01	1	1.84E-13	3.30E-13	5.58E-01	0.99	7.60E-12	1.61E-11	4.72E-01	1.52
Am-241	1.98E-11	3.30E-11	6.00E-01	1	8.55E-08	3.03E-08	2.82E+00	1	1.85E-08	2.51E-09	7.37E+00	1.51
U-238	4.44E-10	3.84E-10	1.16E+00	1	2.28E-08	2.10E-09	1.09E+01	1	1.37E-09	6.12E-10	2.24E+00	1.52
Pu-239	5.74E-13	3.96E-13	1.45E+00	1	8.27E-08	3.63E-08	2.28E+00	0.99	1.80E-08	3.12E-09	5.77E+00	1.52
Ac-227	6.38E-09	4.56E-09	1.40E+00	1	1.28E-06	4.05E-07	3.16E+00	1	7.40E-08	1.49E-08	4.97E+00	1.52

[a)] Shading identifies areas of larger differences between the results of the two models.

[b)] RESRAD/CERISE: Ratio of RESRAD-RECYCLE results to CERISE results.

[c)] Adjusted Ratio: The calculated ratio of RESRAD-RECYCLE results to CERISE results if the same dose conversion factor and radionuclide partitioning factor were used in dose calculation. Calculated by adjusting the RESRAD/CERISE ratio with the corresponding ratio of dose conversion factor and radionuclide partitioning factor.

Table 8. *Phase I dose calculation results for the ingot handling worker scenario* [a)].

Radionuclide	External radiation (Sv)				Inhalation (Sv)				Ingestion (Sv)			
	RESRAD-RECYCLE	CERISE	RESRAD/ CERISE [b)]	Adjusted ratio [c)]	RESRAD-RECYCLE	CERISE	RESRAD/ CERISE [b)]	Adjusted ratio [c)]	RESRAD-RECYCLE	CERISE	RESRAD/ CERISE [b)]	Adjusted ratio [c)]
Co-60	1.17E-08	9.25E-09	1.26E+00	1.13	1.46E-13	2.47E-14	5.91E+00	1.01	9.54E-12	4.38E-12	2.18E+00	1.03
Zn-65	1.80E-11	1.38E-10	1.30E-01	0.10	9.14E-17	2.63E-16	3.48E-01	0.10	3.43E-14	3.34E-13	1.03E-01	0.10
Sr-90	0.00E+00	1.66E-18	0.00E+00	0.00E+00	0.00E+00	9.75E-15	0.00E+00	0.00E+00	0.00E+00	4.17E-12	0.00E+00	0.00E+00
Tc-99	1.61E-14	3.23E-17	4.98E+02	1.01	5.94E-15	1.06E-15	5.60E+00	1.01	5.53E-13	8.80E-14	6.28E+00	1.03
Cs-137	0.00E+00	1.80E-12	0.00E+00	0.00E+00	0.00E+00	1.20E-17	0.00E+00	0.00E+00	0.00E+00	1.77E-14	0.00E+00	0.00E+00
Am-241	0.00E+00	5.61E-13	0.00E+00	0.00E+00	0.00E+00	1.11E-11	0.00E+00	0.00E+00	0.00E+00	2.75E-11	0.00E+00	0.00E+00
U-238	0.00E+00	6.57E-12	0.00E+00	0.00E+00	0.00E+00	7.68E-13	0.00E+00	0.00E+00	0.00E+00	6.72E-12	0.00E+00	0.00E+00
Pu-239	0.00E+00	6.74E-15	0.00E+00	0.00E+00	0.00E+00	1.32E-11	0.00E+00	0.00E+00	0.00E+00	3.44E-11	0.00E+00	0.00E+00
Ac-227	0.00E+00	7.74E-11	0.00E+00	0.00E+00	0.00E+00	1.47E-10	0.00E+00	0.00E+00	0.00E+00	1.64E-10	0.00E+00	0.00E+00

[a)] Shading identifies areas of larger differences between the results of the two models.

[b)] RESRAD/CERISE: Ratio of RESRAD-RECYCLE results to CERISE results.

[c)] Adjusted Ratio: The calculated ratio of RESRAD-RECYCLE results to CERISE results if the same dose conversion factor and radionuclide partitioning factor were used in dose calculation. Calculated by adjusting the RESRAD/CERISE ratio with the corresponding ratio of dose conversion factor and radionuclide partitioning factor.

Table 9. *Phase I dose calculation results for the ingot transport worker scenario [a)].*

Radionuclide	External radiation			
	RESRAD-RECYCLE	CERISE	RESRAD/ CERISE [b)]	Adjusted ratio [c)]
Co-60	2.83E-08	2.26E-08	1.25E+00	1.02
Zn-65	4.28E-11	3.37E-10	1.27E-01	0.10
Sr-90	0.00E+00	4.07E-18	0.00E+00	0.00E+00
Tc-99	8.64E-15	7.89E-17	1.10E+02	1.01
Cs-137	0.00E+00	4.41E-12	0.00E+00	0.00E+00
Am-241	0.00E+00	1.37E-12	0.00E+00	0.00E+00
U-238	0.00E+00	1.60E-11	0.00E+00	0.00E+00
Pu-239	0.00E+00	1.65E-14	0.00E+00	0.00E+00
Ac-227	0.00E+00	1.89E-10	0.00E+00	0.00E+00

[a)] Shading identifies areas of larger differences between the results of the two models.

[b)] RESRAD/CERISE: Ratio of RESRAD-RECYCLE results to CERISE results.

[c)] Adjusted Ratio: The calculated ratio of RESRAD-RECYCLE results to CERISE results if the same dose conversion factor and radionuclide partitioning factor were used in dose calculation. Calculated by adjusting the RESRAD/CERISE ratio with the corresponding ratio of dose conversion factor and radionuclide partitioning factor.

3.3 Conclusions of Phase 1

The execution of Phase 1 of the validation project has most probably been the first time that dose calculation programmes for recycling have been subject to scrutiny and analysis by persons practically engaged in melting and recycling contaminated scrap.

The main result of the Phase 1 activities was that the primary aim of the validation exercise, i.e., comparison of actual doses taken by workers with corresponding values calculated by the codes, could not be realised: The doses were, in every case, below the limits of detection. The calculated doses for all radionuclides, scenarios, and pathways were in the range from 0 to 1.28×10^{-6} Sv. These low doses are below the detection limits of most radiation measurement instruments. Hence, no actual dose measurements were available for 'validation' of the modeling results. Therefore, strictly speaking, the phase I exercise was not a model validation exercise; rather, it was a benchmarking exercise because only RESRAD-RECYCLE and CERISE modeling results were compared.

Phase 2 of the project was originally planned to be a repetition of Phase 1. After the execution of Phase 1, a different approach was discussed. While Studsvik melts scrap metal with residual radioactivity for the recycle of the metal, it also melts metal with a higher level of radioactivity for the purpose of volume reduction of the metal. This possibility was developed into a proposal for a new Phase 2. The new Phase 2 was different from the Phase 2 in the original project proposal, where Phase 2 should have been a repetition of Phase 1. This new Phase 2 was executed, as described in the following section.

4 Phase 2 activities

As described earlier, Phase 2 was originally planned to be a repetition of Phase 1, but it was changed to melt an object with high enough activity to give detectable doses to workers.

4.1 Object

The chosen object was a stainless steel fuel rack from a Swedish nuclear power plant, which had been packed into a 20 foot container. The maximum dose rate on the outside of the container was 0.2 mSv/h. The rack had a total mass of 3.4 (metric) tons. Nuclide specific measurements (made from outside the package) indicated an average radioactivity content of 109 kBq/kg, mostly Co-60.

Earlier measurements on ingots at Studsvik had shown a linear relationship between activity concentration (Bq/kg) and surface dose rate (µSv/h). These measurements had been made up to a concentration of 21 kBq/kg. By linear extrapolation, it was expected that a concentration of 109 kBq/kg should give a surface dose of about 50 µSv/h on the ingots after melting. The surface dose rates on the racks before melting would be significantly higher. This implied that the personnel engaged in the various stages of the melting operations would be exposed to measurable doses.

4.2 Melting operations

The rack was delivered in the container to Studsvik. Normally, the operations comprising the melting process consist of the following:

- reception of package/unpacking;
- segmenting of racks (plasma torch);
- storage of segmented pieces;
- melting;
- slag handling;
- filter dust handling;
- handling and transport of ingots; and
- storage of ingots.

In the treatment of the fuel rack, the segmented pieces were taken directly for melting. The filter dust quantity was too small to be collected and ‘handled’, and storage of the ingots was not considered.

In April 2000, a new induction furnace was completely operational and the calculations of Phase 2 were made with the characteristics of the new installation. A new set of background dose rate measurements was made. The off gas system filters were back-flushed before the melting.

A sectional view of the Studsvik melting furnace is shown in Attachment 5. Photographs in Attachment 6 illustrate some events of the Phase 2 operations.

4.3 Dose rate/dose/activity measurements

The following parameters were recorded during the various operations:

- Dose (personal)
  - Electronic (display)
    (A technical description of such dosimeters is given in Attachment 7)
  - The personnel also wore TLDs as part of the regulatory requirements
- Dose rates
  - Handheld for surface and 1-m distance measurements
  - Online recording of general dose rate, placed at representative positions
- Air sampling with 5 μm filter
  - Personal air sampling device attached to one or two people
  - General room measurements
  - Filters nuclide specifically analysed
- Loose contamination
  - Object and room surfaces.

After the various operations, dust from the ventilation system was weighed, sampled and nuclide-specifically analysed. Ingots and slag from the melting operation were also weighed, sampled and nuclide-specifically analysed.

In order to make direct comparisons with the calculations, the electronic dosimeters were provided with dose codes corresponding to various operations, as follows:

Dose code 610: Transport of container into workshop.
Dose code 611: Opening of container, lifting of fuel rack, removing of plastic foil wrapping, setting up rack for cutting.
Dose code 612: Segmenting of fuel rack (plasma torch).
Dose code 613: Melting, slagging, pouring into moulds.
Dose code 614a: Handling of ingots in moulds (i.e. shielded).
Dose code 614b: Handling of ingots after cooling and removal from moulds (i.e. unshielded).
Dose code 615: Transport of ingots to temporary storage in Studsvik.
Dose code 617: Slag handling.

Details of the measurements are shown in Attachment 4. This attachment also shows the actual basic data, such as time, distance, number of workers, etc., which were used as the basis for calculations.

The measurements showed that segmenting was the work operation that gave the highest dose, almost 65 % of the total dose incurred, while melting itself accounted for only about 13 %. The TLD measurements were, in every case, less than 0.1 mSv, the limit for registration.

4.4 Calculation of Phase 2 melting

Phase II of the validation project involved evaluating doses from the melting of a stainless steel nuclear fuel rack from a Swedish nuclear power plant. The rack was shipped to the Studsvik facility in a 20-foot-long container. The maximum dose rate measured on the outside of the container was 0.2 mSv/h. Radionuclide-specific measurements indicated an average radioactivity concentration of 109 Bq/g, mostly Co-60. Other radionuclides included Sb-125, Cs-134, Cs-137, and Eu-154.

The fuel rack was melted in Studsvik and actual radiation dose rates were measured for each of the various operations involved in the process. Dust from the ventilation system and slag from the melting operation were also sampled and analysed. To facilitate dose calculations, the geometry of the radiation source, exposure distance between the source and the worker, and the time span of each operation were developed on the basis of the real operations.

All the parameter values used in the dose calculations were based on the Studsvik values except for the inhalation and ingestion dose conversion factors, for which the FGR values and the European Directive values were used by RESRAD-RECYCLE and CERISE, respectively.

4.4.1 SCENARIO DESCRIPTION

Eight exposure scenarios were developed to account for the various operations conducted during the melting process. These eight scenarios evaluated doses to the following work groups: (1) scrap truck drivers, (2) scrap unloaders, (3) scrap cutters/sorters, (4) furnace operators, (5) ingot handlers A (during ingot cooling in moulds), (6) ingot handlers B (after ingot cooling and removal from moulds), (7) ingot fork driver, and (8) slag handler.

The truck drivers transported the container with the fuel rack into the melting facility at Studsvik. The scrap unloaders unloaded the fuel rack from the container. The scrap cutters/sorters dissembled the fuel rack and cut it into smaller pieces that could be fed to the furnace. The cutting process produced a small quantity of swarf. The furnace operators loaded the fuel rack to the furnace and operated the furnace. After the ingot melt was poured into vertical moulds, the ingot handlers A moved the ingot (in moulds) away for cooling. After cooling, ingot handlers B removed the solid ingots from moulds. The solid ingots were then put on wooden pallets in a storage area by the ingot fork driver. During melting of the fuel rack, slag from the melt surface was removed by the slag handler with a special tool and was put in a metallic box in the same area for further handling. Photographs of the various operations are included in Attachment 6.

4.4.2 MASS PARTITIONING FACTORS

Mass partitioning factors used in dose calculations were developed from the measured masses of the ingot product, the slag product, and filter dust (listed in Table 10) and with application of the principle of mass conservation. The cutting swarf (2 kg) was neglected in RESRAD-RECYCLE and CERISE calculations because (1) its mass was very small compared with the mass of the fuel rack (the initial throughput) (> 3 355 kg), and (2) the swarf is not a product of the melting process. Neglecting the cutting swarf had very little effect on the values of the partitioning factors.

For RESRAD-RECYCLE calculations, the partitioning factors for ingot and slag were obtained by normalizing the mass of ingot and slag, respectively, with a total mass of 3 355.2 kg (not including the weight of the cutting swarf). The partitioning factor for filter dust was then calculated on the basis that the sum of the three partitioning factors should be 1. For CERISE calculations, the partitioning factors were obtained by normalizing the mass of ingot, slag, and filter dust, respectively, with a total mass of 3 357.2 kg (including the weight of the cutting swarf). Therefore, the sum of the three partitioning factors is very close to, but not exactly, 1. The mass partitioning factors used by RESRAD-RECYCLE were 98.35 % for ingot, 1.64 % for slag, and 0.01 % for filter dust. The partitioning factors used by CERISE were 98.3 % for ingot, 1.65 % for slag, and 0.004 % for filter dust.

4.4.3 RADIONUCLIDE PARTITIONING FACTORS

Radionuclide partitioning factors used for dose calculations were developed on the basis of the measured activity contents in ingot, slag, and dust filters (listed in Table 10). Like the calculations for mass partitioning factors, for RESRAD-RECYCLE dose calculations, the measured radionuclide contents in the cutting swarf were neglected and subtracted from the total contents. The total radionuclide contents, after the subtraction, were used to normalize the radionuclide contents in ingot and slag, respectively. The partitioning factor for baghouse filter was then calculated by assuming a sum of 1 for the three partitioning factors. For CERISE dose calculations, the partitioning factors were calculated by normalizing the radionuclide content in ingot, slag, and filter dust, respectively, with the total content of radionuclides (including those in the cutting swarf). The calculated radionuclide partitioning factors are listed in Table 11.

Radionuclide concentrations in the fuel rack were calculated from information on total mass and amount of radionuclides in the three melting products. Concentrations in the fuel rack were calculated as 157 Bq/g for Co-60, 3.66 Bq/g for Sb-125, 0.027 Bq/g for Cs-134, 10.82 Bq/g for Cs-137, and 0.0060 Bq/g for Eu-154.

4.4.4 EXPOSURE PATHWAYS

Exposure pathways considered for dose calculations were external radiation, inhalation, and ingestion. For the ingot handler and ingot fork driver, radiation exposures from the inhalation and ingestion pathways were insignificant because little dust loading occurred during the operations. For the other scenarios, exposures from inhalation and ingestion were considered through the use of an inhalation rate of 1.2 m^3/h and an ingestion rate of 0.00625 g/h.

4.4.5 SOURCE GEOMETRIES AND EXPOSURE PARAMETERS

Table 12 lists the source geometries and exposure parameters used by RESRAD-RECYCLE and CERISE for dose calculations. Along with the scenario names, the dose codes used by Studsvik in dose measurements are also listed. For the ingot handler and ingot fork driver, source dimensions used by CERISE were different from those used by RESRAD-RECYCLE. This difference was due to different perceptions regarding representing a radiation source of five ingots with a cylindrical geometry. CERISE assumed a full cylinder with a thickness of 100 cm and a radius of 16.9 cm for the ingot handler scenarios. RESRAD-RECYCLE, on the other hand, assumed a full cylinder with a thickness of 100 cm, and a radius of 40 cm. A half cylinder with a thickness of 120 cm and a radius of 43.7 cm was assumed by CERISE for the ingot fork driver scenario, while RESRAD-RECYCLE assumed a full cylinder with a thickness of 250 cm and a radius of 23 cm.

For the scrap truck driver scenario, the external radiation was considered to be attenuated by the truck cab, which was made of steel and had a density of 7.86 g/cm^3 and a thickness of 0.3 cm. During the handling of ingot melt, ingot handlers A were shielded from radiation by the moulds, which had a density of 7.86 g/cm^3 and a thickness of 8 cm. The slag handler was shielded by the slag container, which had a density of 7.86 g/cm^3 and a thickness of 1.2 cm. The ingot fork driver took five ingots to storage at a time; therefore, dimensions of the radiation source were developed to consider potential radiation exposure from the five ingots.

4.4.6 DOSE CONVERSION FACTORS

The internal dose conversion factors used in RESRAD-RECYCLE calculations were obtained from FGR 11; those used in CERISE calculations were obtained from EU Basic Safety Standards (Council Directive 96/29/EURATOM). They are listed in Table 13 for comparison. Dose conversion factors for external radiation calculated by the two codes are listed in Table 14.

4.4.7 RESULTS AND COMPARISONS

Calculation and measurement dose results for the eight exposure scenarios are listed in Tables 15–22. Measured radiation exposures, excluding background levels, are available for four operational activities and are compared with the calculation results.

Among the three exposure pathways analysed, radiation exposure from the external radiation pathway was far more significant than radiation exposure from the two internal radiation pathways (inhalation and ingestion). Radiation exposures incurred by the scrap unloaders and scrap cutters/sorters were greater than those incurred by the other workers because of the closer exposure distances and longer exposure times experienced by the scrap unloaders and scrap cutters/sorters.

External radiation doses calculated by RESRAD-RECYCLE were smaller than those calculated by CERISE for the scrap truck drivers, scrap unloader, and scrap cutter/sorter. For the furnace operator and ingot handler scenarios, in contrast, RESRAD-RECYCLE results were greater than CERISE results. For the ingot fork driver and slag handler, dose results from the two codes were about the same. The differences in dose results were within a factor of 6. Larger differences were observed for the two ingot handling scenarios because of different geometries and dimensions assumed in the dose calculations. The radiation source assumed by RESRAD-RECYCLE had larger dimensions; therefore, dose results from RESRAD-RECYCLE are greater than CERISE results.

Table 10. *Mass and radionuclide inventories measured for the melting products in Phase 2.*

Inventories	Ingot	Cutting Swarf	Slag	Filter Dust	Total
Mass (kg)	3 300	2	55	0.2	3 357.2
Radionuclides (MBq)					
Co-60	518	0.34	8.7	0.02	527
Sb-125	12.2	0.01	0.08	-	12.3
Cs-134	– [a]	–	0.09	-	0.09
Cs-137	–	–	36.3	-	36.3
Eu-154	–	–	0.02	-	0.02

[a] A dash (–) indicates activity was too low to be detected.

Table 11. *Radionuclide partitioning factors for Phase 2 calculations.*

Radionuclides	Ingot		Slag		Filter Dust	
	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Co-60	9.83E-01	9.83E-01	1.65E-02	1.65E-02	1.00E-04	3.80E-05
Sb-125	9.93E-01	9.92E-01	6.50E-03	6.50E-03	1.00E-04	4.88E-05
Cs-134	0	0	1.00	1.00	0	0
Cs-137	0	0	1.00	1.00	4.00E-05	4.00E-05
Eu-154	0	0	1.00	1.00	0	0

Table 12. *Source geometry and exposure parameters used by RESRAD-RECYCLE and CERISE for Phase 2 dose calculations.*

Worker Scenario	Dose Codes	Source Geometry	Mass (t)	Density (g/cm^3)	Thickness (cm)	Radius (cm)	Distance (cm)	Time (h)	Source material for the external pathway [a]	Source material for the internal pathways [a]	Dust loading (g/m^3)	Number of workers
Scrap truck driver [b]	610	1 full cylinder	3.3	0.13	400	145	150	0.15	Scrap	Scrap	1×10^{-4}	2
Scrap unloader	611	1 full cylinder	3.3	0.13	400	145	50	3.7	Scrap	Scrap	1×10^{-4}	2
Scrap cutter/sorter	612	1 full cylinder	3.3	0.13	400	145	30	9.95	Scrap	Scrap	1×10^{-3}	2
Furnace operator [c]	613	1 full cylinder	3.3	7.86	100	40	145/90 [d]	6.3	Scrap	Baghouse filter	1×10^{-3}	2
Ingot handling A (shielded) [e,f]	614 A	1 full cylinder	3.2	7.86	100	40	100	0.7	Ingot	none	0	1
Ingot handling B (unshielded) [e]	614 B	1 full cylinder	3.2	7.86	100	40	50	1.5	Ingot	none	0	1
Ingot fork driver [g]	615	1 full cylinder	3.2	7.86	250	23	200	0.2	Ingot	none	0	1
Slag handler [h]	617	1 full cylinder	0.06	1.5	20	25	50	0.2	Slag	Slag	1×10^{-3}	1

a) Radionuclide concentrations in the specified materials were used in the dose calculations for the various worker scenarios.

b) External radiation was attenuated by a steel shielding with a density of 7.86 g/cm^3 and a thickness of 0.3 cm.

c) External radiation was attenuated by a concrete shielding with a density of 2.8 g/cm^3 in RESRAD-RECYCLE and 2.35 g/cm^3 in CERISE and a thickness of 12 cm.

d) Off-center distance.

e) Source dimensions used by CERISE for dose calculations were 100 cm for thickness and 16.9 cm for radius.

f) External radiation was attenuated by a steel shielding material with a density of 7.86 g/cm^3 and a thickness of 8 cm.

g) Source dimensions used by CERISE for dose calculations were 120 cm for thickness and 43.7 cm for radius for a half cylinder.

h) External radiation was attenuated by a steel shielding material with a density of 7.86 g/cm^3 and a thickness of 1.2 cm.

Table 13. *Internal dose conversion factors used for Phase 2 calculations.*

Radionuclides	Ingestion (Sv/Bq)		Inhalation (Sv/Bq)	
	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Co-60	7.28E-09	3.40E-09	5.91E-08	1.00E-08
Sb-125	7.59E-10	1.30E-09	3.30E-09	5.58E-09
Cs-134	1.98E-08	1.90E-08	1.25E-08	6.60E-09
Cs-137	1.35E-08	1.30E-08	8.63E-09	4.60E-09
Eu-154	2.58E-09	5.30E-09	7.73E-08	5.30E-08

Table14. *External dose conversion factors calculated for Phase 2 scenarios.*

Radionuclides	External Dose Conversion Factors [(Sv/h)/(Bq/g)]							
	Scrap Truck Driver		Scrap Unloader		Scrap Cutter/Sorter		Furnace Operator	
	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Co-60	5.60E-08	9.62E-08	1.42E-07	2.31E-07	1.79E-07	2.73E-07	1.11E-08	9.27E-08
Sb-125	9.51E-09	1.24E-08	2.48E-08	2.98E-08	3.14E-08	3.53E-08	1.65E-09	1.14E-08
Cs-134	3.58E-08	5.24E-08	9.19E-08	1.26E-07	1.16E-07	1.49E-07	6.53E-09	4.86E-08
Cs-137	1.30E-08	1.86E-08	3.33E-08	4.46E-08	4.22E-08	5.28E-08	2.35E-09	1.72E-08
Eu-154	2.61E-08	4.38E-08	6.80E-08	1.05E-07	8.60E-08	1.24E-07	5.11E-09	4.16E-08

Radionuclides	External Dose Conversion Factors [(Sv/h)/(Bq/g)]							
	Ingot Handler A		Ingot Handler B		Ingot Fork Driver		Slag Handler	
	RESRAD-RECYCLE	CERISE[b]	RESRAD-RECYCLE	CERISE[b]	RESRAD-RECYCLE	CERISE[b, c]	RESRAD-RECYCLE	CERISE
Co-60	1.06E-09	5.13E-09	9.98E-08	1.93E-08	3.09E-09	3.08E-09	2.22E-08	3.09E-08
Sb-125	3.56E-11	6.29E-10	1.51E-08	2.37E-09	4.62E-10	3.77E-10	3.34E-09	4.35E-09
Cs-134	2.58E-10	2.69E-09	5.94E-08	1.01E-08	1.82E-09	1.61E-09	1.33E-08	1.78E-08
Cs-137	8.15E-11	9.49E-10	2.14E-08	3.58E-09	6.56E-10	5.70E-10	4.75E-09	6.37E-09
Eu-154	4.06E-10	2.30E-09	4.62E-08	8.67E-09	1.43E-09	1.38E-09	1.01E-08	1.44E-08

a) Shading identifies areas of larger differences between the results of the two models.

b) Source dimensions used by CERISE for dose calculations were different from those used by RESRAD-RECYCLE. See Table 12 for information on the dimensions.

c) Values listed were obtained by dividing the reported CERISE values (for a full cylinder) by a factor of 2 to account for the half-cylinder geometry assumed by CERISE.

Table 15. *Calculated doses (Sv) for Phase 2 scrap truck driver scenario (dose code 610).*

Radionuclides	RESRAD-RECYCLE			CERISE		
	External radiation	Inhalation	Ingestion	External radiation	Inhalation	Ingestion
Co-60	1.23E-06	1.57E-11	1.74E-11	1.97E-06	2.65E-12	4.69E-10
Sb-125	4.62E-09	1.92E-14	3.98E-14	5.63E-09	3.26E-14	3.95E-12
Cs-134	1.22E-10	5.12E-16	7.31E-15	1.67E-10	2.71E-16	4.07E-13
Cs-137	2.08E-08	1.66E-13	2.34E-12	2.77E-08	8.84E-14	1.30E-10
Eu-154	2.24E-11	7.97E-16	2.40E-16	3.52E-11	5.50E-16	1.08E-14
Total (Individual)	1.26E-06	1.59E-11	1.97E-11	2.01E-06	2.77E-12	6.03E-10
Total (Collective)	2.52E-06	3.16E-11	3.94E-11	4.01E-06	5.54E-12	1.21E-09

Table 16. *Calculated doses (Sv) for Phase 2 scrap unloader scenario (dose code 611).*

Radionuclides	RESRAD-RECYCLE			CERISE		
	External radiation	Inhalation	Ingestion	External radiation	Inhalation	Ingestion
Co-60	7.72E-05	3.86E-10	4.28E-10	1.26E-04	6.53E-11	1.16E-08
Sb-125	2.97E-07	4.74E-13	9.82E-13	3.58E-07	8.03E-13	9.74E-11
Cs-134	7.74E-09	1.26E-14	1.80E-13	1.06E-08	6.69E-15	1.00E-11
Cs-137	1.32E-06	4.10E-12	5.77E-11	1.76E-06	2.18E-12	3.21E-09
Eu-154	1.44E-09	1.97E-14	5.91E-15	2.24E-09	1.36E-14	2.67E-13
Total (Individual)	7.88E-05	3.91E-10	4.87E-10	1.28E-04	6.83E-11	1.49E-08
Total (Collective)	1.56E-04	7.82E-10	9.74E-10	2.56E-04	1.37E-10	2.98E-08

Table 17. *Calculated doses (Sv) for Phase 2 scrap cutter/sorter scenario (dose code 612).*

Radionuclides	RESRAD-RECYCLE			CERISE		
	External Radiation	Inhalation	Ingestion	External Radiation	Inhalation	Ingestion
Co-60	2.62E-04	1.04E-08	7.81E-08	3.99E-04	1.76E-09	3.11E-08
Sb-125	1.01E-06	1.28E-11	1.79E-10	1.14E-06	2.16E-11	2.62E-10
Cs-134	2.64E-08	3.40E-13	3.29E-11	3.38E-08	1.80E-13	2.70E-11
Cs-137	4.49E-06	1.10E-10	1.05E-08	5.61E-06	5.86E-11	8.63E-09
Eu-154	4.90E-09	5.29E-13	1.08E-12	7.13E-09	3.65E-13	7.17E-13
Total (Individual)	2.68E-04	1.05E-08	8.89E-08	4.06E-04	1.96E-09	4.00E-08
Total (Collective)	5.36E-04	2.10E-08	1.78E-07	8.12E-04	3.92E-09	8.00E-08

Table 18. Calculated doses (Sv) for Phase 2 furnace operator scenario (dose code 613).

Radionuclides	RESRAD-RECYCLE			CERISE		
	External Radiation	Inhalation	Ingestion	External Radiation	Inhalation	Ingestion
Co-60	1.97E-06	6.57E-09	4.95E-08	8.06E-07	7.09E-10	1.26E-08
Sb-125	2.96E-09	8.08E-12	1.13E-10	2.17E-09	1.12E-11	1.36E-10
Cs-134	1.13E-10	0	0	6.53E-11	0	0
Cs-137	1.78E-08	2.79E-11	2.67E-09	1.07E-08	2.57E-11	3.79E-09
Eu-154	3.17E-11	0	0	1.41E-11	0	0
Total (Individual)	1.99E-06	6.61E-09	5.22E-08	8.19E-07	7.46E-10	1.65E-08
Total (Collective)	3.98E-06	1.32E-08	1.04E-07	1.64E-06	1.49E-09	3.31E-08

Table 19. Calculated doses (Sv) for Phase 2 ingot handling scenario (dose code 614A).

Radionuclides	RESRAD-RECYCLE			CERISE		
	External Radiation	Inhalation	Ingestion	External Radiation	Inhalation	Ingestion
Co-60	1.09E-07	0	0	1.90E-08	0	0
Sb-125	8.14E-11	0	0	5.19E-11	0	0
Cs-134	0	0	0	0	0	0
Cs-137	0	0	0	0	0	0
Eu-154	0	0	0	0	0	0
Total (Individual)	1.10E-07	0	0	1.90E-08	0	0
Total (Collective)	1.10E-07	0	0	1.90E-08	0	0

Table 20. Calculated doses (Sv) for Phase 2 ingot handling scenario (dose code 614B).

Radionuclides	RESRAD-RECYCLE			CERISE		
	External Radiation	Inhalation	Ingestion	External Radiation	Inhalation	Ingestion
Co-60	2.20E-05	0	0	4.28E-06	0	0
Sb-125	7.42E-08	0	0	1.17E-08	0	0
Cs-134	0	0	0	0	0	0
Cs-137	0	0	0	0	0	0
Eu-154	0	0	0	0	0	0
Total (Individual)	2.21E-05	0	0	4.29E-06	0	0
Total (Collective)	2.21E-05	0	0	4.29E-06	0	0

Table 21. *Calculated doses (Sv) for Phase 2 ingot fork driver scenario (dose code 615).*

Radionuclides	RESRAD-RECYCLE			CERISE		
	External Radiation	**Inhalation**	**Ingestion**	**External Radiation**	**Inhalation**	**Ingestion**
Co-60	9.10E-08	0	0	9.08E-08	0	0
Sb-125	3.02E-10	0	0	2.48E-10	0	0
Cs-134	0	0	0	0	0	0
Cs-137	0	0	0	0	0	0
Eu-154	0	0	0	0	0	0
Total (Individual)	9.13E-08	0	0	9.10E-08	0	0
Total (Collective)	9.13E-08	0	0	9.10E-08	0	0

Table 22. *Calculated doses (Sv) for Phase 2 slag handling scenario (dose code 617).*

Radionuclides	RESRAD-RECYCLE			CERISE		
	External Radiation	**Inhalation**	**Ingestion**	**External Radiation**	**Inhalation**	**Ingestion**
Co-60	6.57E-07	2.10E-10	1.58E-09	6.87E-07	3.55E-11	6.30E-10
Sb-125	8.58E-10	1.02E-13	1.43E-12	8.40E-10	1.72E-13	2.09E-12
Cs-134	3.69E-09	4.17E-13	4.03E-11	3.73E-09	2.21E-13	3.31E-11
Cs-137	6.20E-07	1.35E-10	1.29E-08	6.23E-07	7.19E-11	1.06E-08
Eu-154	7.07E-10	6.48E-13	1.32E-12	7.58E-10	4.47E-13	8.80E-13
Total (Individual)	1.28E-06	3.46E-10	1.45E-08	1.31E-06	1.08E-10	1.13E-08
Total (Collective)	1.28E-06	3.46E-10	1.45E-08	1.31E-06	1.08E-10	1.13E-08

5 Comparison of calculations with measurements

Table 23 shows a comparison of the RESRAD-RECYCLE and CERISE calculation results with the electronic dosimeter measurements for each dose code. The TLD measurements were in every case less than the limit for registration, 0.1 mSv. The table has been divided into doses taken during work preparatory to melting and doses taken during and after melting.

Some comments on Table 23:

- Significant measured doses are noted only for the following scenarios: unloading of the fuel rack (611) and its cutting (612) and for the melting operations (613). For the other scenarios, measured doses are not given but these are very low due to the short duration of work station activity (fuel rack transport into the building, ingot and slag handling, ingot truck transport).
- The part sum of doses shows that the pre-melting preparatory work accounted for 84 % of the total doses, while the melting itself with ingot and slag handling were responsible for the remaining 16 %.
- There is an overestimation by the codes for the doses under dose codes 611, 612 and 614b, covering 86 % of the total dose; and an underestimation of the doses under codes 613 and 617.

5.1 Possible explanations and their significance

5.1.1 FUEL RACK CUTTING SCENARIO

For CERISE and RESRAD-RECYCLE modelling, some approximations need to be done on some parameters. We focus on the scenario ‘cutting’ (612), which gives relevant calculated and measured doses. The remarks given below are not a sensitivity analysis but give some explanations on the differences between calculations and measurements.

Modelling of the source geometry

The fuel rack arrived in Studsvik in a 20 feet container. Dimension of fuel rack are 2.4 m width, 2.8 m height and 4 m thickness.

For modelling, the parallel-piped rack is simulated as a 3.4-ton cylinder of the same volume with a radius of 145 cm, a thickness of 400 cm because in both CERISE and RESRAD-RECYCLE codes, the parallel-piped volume is not taken into account.

Estimation of the density

The estimated density of 0.126 g/cm^3 is the ratio of the fuel rack weight on the fuel rack volume. This density value is far from the theoretical density value for steel material.

In CERISE code, the density parameter affects the calculation of other parameters as the external dose conversion factor or the mass absorption coefficient μ/ρ_m (function of energies and density of the material).

Table 23. *Phase 2, comparison of doses per dose code between RESRAD-RECYCLE/CERISE and electronic dosimeter measurements. (All values in micromanSv.)*

Code		RESRAD-RECYCLE	CERISE	Measurements: Incl. back-ground	Measurements: Excl. back-ground	Measurements: Background	Ratios to measurements (excl. background): RESRAD-RECYCLE	Ratios to measurements (excl. background): CERISE
610	Transport of container into workshop	2.5	4	1	< 1			–
611	Opening of container	156	256	43	38	5.2	4.1	6.7
612	Segmenting	536	812	121	107	13.9	5.0	7.6
Part sum regarding work preparatory to melting		**694.5**	**1 072**	**165**	**145**		**4.2**	**7.4**
613	Melting (with shielding)	4	1.7	32	22	10.1	0.18	0.08
614a	Handling of ingots in moulds	0.1	0.02	1	< 1	0.1		–
614b	Handling of ingots after removal from moulds	22	4.3	4	4	< 0.1	5.5	1.1
615	Transport of ingots to storage	0.1	0.1			<0.1		–
617	Slag handling	1.3	1.3	2	1.8	0.2	0.7	0.7
Total		**722**	**1 080**	**204**	**173**		**4.2**	**6.2**

If the density taken into account is different from the pure material density, an interpolation is made. With such a low apparent density, the interpolation values may not be correct.

To quantify the influence of the density, some calculations with MICROSHIELD code were done for comparison with CERISE results. For densities lower than 1 g/cm^3 MICROSHIELD gives doses about 1.6 times lower than CERISE doses. This factor could explain, in part, the ratio between CERISE calculations and measurements for the scrap processor scenarios (610–612).

Estimation of the mean distance to the source

The mean distance of worker to fuel rack edge is 30 cm during cutting (code 612) for CERISE calculations. This mean distance is obviously conservative and during the cutting, the worker could be not so close to the fuel rack. For a distance of the worker to the fuel rack of 70 cm instead of 30 cm, the calculated dose will be lower by a factor of 1.2. Also, only one of the two workers did the actual cutting.

Dimensions of source

In CERISE modelling we have considered that the contaminated fuel rack have the same dimensions during all the cutting operation. In the real situation, the contaminated source decreases in length and depth during the cutting process.

To estimate the influence of this fact, we have considered the 612 scenario but with four varying length sources between 1–4 m during a total of 9.95 hours. Taking into account only the length change from 4 m to 1 m, the dose during the cutting decreases by a factor 0.76. The CERISE dose is an overestimate of about 1.3.

We have also to take into account the radius decrease from 145 cm to only a few centimetres. Taking both these dimensional factors into account, (decrease of the fuel rack length and radius) the final dose decrease of about 1.7.

In conclusion, by taking into account the decrease of density, mean distance from source and source volume parameters, the calculated doses are reduced of about 3.2 (1.6 x 1.2 x 1.7) as compared to the 7.6 factor given in Table 19. This gives a ratio of 2.3 between calculated and measured values.

Other important factors, which have been difficult to identify, are the exact number of workers and their positions during the process.

5.1.2 FURNACE SCENARIO

For the fuel rack part melting (scenario 613), the CERISE doses are lower than the measured dose in the plant by a factor of about 12.

For the scenario we considered a mean distance of operator from the furnace edge of 50 cm. In some operations, such as putting the small cut pipes into the furnace, the operator is closer to the furnace edge, sometimes only a few centimetres. During the melting, the furnace is sometimes tilted and the shielding due to the refractory walls has less influence.

The mean distance from the contaminated melt included the distance parameter from one part and the decrease of the shielding impact from another part when the worker is at the furnace edge. Both factors give an increase of the dose of about a factor 10.

6 Conclusions

The aim of the validation project was to compare the measured radiation doses to workers and the public, when subjected to a certain sequence of exposures, with the doses for the same sequence calculated by the RESRAD-RECYCLE and CERISE codes respectively. To represent the exposure sequence, a consignment of contaminated scrap was melted at the Studsvik RadWaste melting facility; ingots released under the regulations of the Swedish Radiation Protection Authority were transported to Åkers AB for remelting with fresh (uncontaminated) scrap and used in the manufacture of rolls.

The first phase of the project – i.e. melting of contaminated scrap at Studsvik, transport of released ingots to Åkers, and melting of ingots with uncontaminated scrap at Åkers for the manufacture of rolls – was executed according to the original plan. Calculations were made with the two codes, reflecting the melting in Studsvik and the transport to Åkers. However, no comparisons could be made, as the doses were, in every case, below the limits of detection.

A second phase was executed, involving the melting of a 3.4 ton stainless steel fuel rack with about 576 MBq (mostly Co-60) of radioactivity (i.e. about 157 Bq/g) at the Studsvik facility. The dose modellers were present during the entire Phase 2 operations, to ensure that the data fed into the programmes should be as correct as possible.

The comparison of the calculation results indicates that, even with a carefully controlled reflection of reality with respect to geometry and exposure time and with a 'best judgement' choice of densities for each operation, the calculation programmes have tended to overestimate the measured values of the total dose by a factor 4 to 6, i.e. about an order of magnitude. An obvious explanation is the fact that the workers are not static, they move about constantly, changing the geometry, thus not taking the calculated doses.

Other practical aspects difficult to reflect exactly in the calculations are:

- modelling of the source geometry (during cutting);
- estimation of the density (during cutting);
- estimation of the mean distance to the source (during cutting and melting);
- dimensions of the source (during cutting and melting); and
- estimation of shielding thickness (during melting).

The programmes assume a source with mass specific distribution of radioactivity (Bq/g), while, in most cases, the actual object has the corresponding total activity concentrated on its surface. This should lead to an underestimation of the dose uptake by the workers involved in segmenting. However, the conservatism of the above listed factors obviously more than compensates for this, as is shown by the overestimation of the doses in total by the codes.

It seems reasonable to state that the use of 'enveloping' scenarios, which necessarily cover a wide range of scenarios in connection with the calculation of clearance levels, would tend to accentuate this tendency of overestimation of dose uptake in most individual cases of recycling by melting. Taking into account the sensitivity of the modelling and the various parameters in the analysis under Section 5.1, the estimated doses can be, say, one or even more orders of magnitude higher than those actually taken.

It should be pointed out that the Phase 2 melting was performed on a typical reactor system component with only gamma emitters, with Co-60 and Cs-137 as the dominant radionuclides. The dose incurred was almost exclusively by external exposure. This is in agreement with the dose modelling results.

A side aspect of the execution of the Validation Project – specifically the background measurements – was the revelation of radioactivity in unexpected places: the paint used for the painting of moulds at Åkers (3–5 Bq/g), the slag binding product (twice background radiation), the stamp mass, insulation and new asphalt at the Studsvik furnace (all at three to four times background). This serves to illustrate the undetected omnipresence of radioactivity in the human habitat at dose rate levels considerably higher (up to 400 % over background) than the levels (ca 1 % over background) at which the currently proposed clearance criteria are based on.

Finally, it is important to note that the degree of overestimation (a factor of 4–6), as recorded in the validation project, is generally regarded as 'acceptable' by dose modellers. The results will most probably not lead to any revision or refinement of these codes. For the nuclear decommissioner and the other producers of large volumes of only slightly radioactively contaminated material, the clearance levels resulting from such a degree of conservatism can lead to huge amounts of material unnecessarily being condemned to burial as radioactive waste. Considering that most such producers transfer their costs to the public, it is society at large that will foot the bill for this exercise in conservatism.

Attachment 1

Project team

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Attachment 2

Brief descriptions of companies/ programmes

A2.1 Companies

A2.1.1 STUDSVIK RADWASTE AB

Studsvik RadWaste AB in Sweden has been melting contaminated metal scrap from the nuclear industry since 1987. Hitherto, some 3 500 t of carbon steel, stainless steel, brass and aluminium has been melted. At the melting facility, the scrap is segmented and melted (separately material-wise) in 3 t (for iron and steel) or about 500 kg (aluminium and brass) lots and the nuclide specific concentration of radioactivity in each melt is measured. The slag and filtered dust are conditioned and treated as radioactive waste. The ingots resulting from each melt are stored, until the radioactivity has decayed below a level prescribed by the Swedish Radiation Protection Institute (currently a maximum of 0.8–1 Bq/g, beta or gamma nuclides). The ingots are, after certification by the authorities, released in batches of some tens of tons, for remelting at commercial melting facilities. The average concentration in such batches is generally 0.5–0.6 Bq/g. At the commercial melters, the ingots are used as feed material and mixed with other scrap or raw material for producing new iron, steel or aluminium that will later be turned into industrial products.

A2.1.2 ÅKERS INTERNATIONAL AB

Åkers was founded almost four centuries ago to cast cannons, which was their main activity for over 250 years. Even before the last cannons had been manufactured, the first rolls had been cast for steel mills. Since then the Åkers Group has grown to become a major manufacturer of rolls for both hot and cold rolling in the international steel and non-ferrous metal industries. It has plants in Sweden, Germany and the USA. The total annual cast roll production capacity is 50 000 t, which makes it the largest supplier of cast rolls in the world. In 1998, Åkers acquired a share majority in Forecast International SA, which manufactures cast and forged rolls in France and Belgium.

Åkers Swedish plant manufactures about 20 000 t of rolls per year. Typical steps in the manufacture of rolls are:

- production of specific alloy steels from scrap, iron and alloying additives,
- setting up of moulds for the vertical centrifugal casting machine,
- pouring of the molten material into the rotating moulds,
- heat treatment
- machining
- inspection/packing for transport.

The steel material for the rolls is produced in 9 induction furnaces with the following capacities:

3	25 t	low frequency furnaces;
5	8 t	high frequency furnaces;
1	1 t	high frequency furnace.

A2.1.3 BELGOPROCESS NV

Belgoprocess is the company that was established to take charge of the activities at the site of the Eurochemic Reprocessing Plant, Dessel, Belgium, after its shut down in 1975. The company is a subsidiary of the Belgian radioactive waste management authority NIRAS-ONDRAF. The company’s activities include the decommissioning of the Eurochemic plant, conditioning radioactive waste, storing conditioned waste and running a centralised waste processing tacility (CILVA) which offers supercompaction and incineration services.

The main process building of the Eurochemic plant is a large rectangular construction of about 80 m long, 27 m wide and 30 m high. The concrete surface is about 55 000 m^2 and its volume is about 12 500 m^3. An industrial process has been developed to separate out the metals (reinforcement and small penetrations), crush the concrete to rubble and sampling the rubble with the aim of release from radiological regulation.

A2.1.4 STUDSVIK STENSAND

Studsvik Stensand is the lead company in the industrial services business unit of the Studsvik Group in the areas of decontamination, health physics, dosimetry, chemical cleaning, dismantlng, waste management, mechanical maintenance and process cleaning. The services are provided mainly to the nuclear power industry, but also to non-nuclear process and manufacturing industries. The nuclear services are for the most part during the refuelling and maintenance outages of power reactors.

The business unit operates mainly in Sweden and Germany and employs about 850 persons.

A2.2 Calculation programmes

A2.2.1 RESRAD-RECYCLE

The RESRAD-RECYCLE family of codes has been developed by the Argonne National Laboratories to assess the radiological doses and associated cancer risks for workers and the public, resulting from exposure to radionuclides. RESRAD-RECYCLE assesses the radiological doses resulting from the recycle of contaminated material or the reuse of contaminated equipment. It considers external exposure, inhalation and ingestion pathways. The model includes 20 worker scenarios and 11 consumer product scenarios. The recycle process is subdivided into the following activities:

- initial transport of scrap,
- smelting,
- transport to fabrication plants,
- product fabrication,
- use of consumer product.

The code takes into account the emissions through the stack during melting, the management of the baghouse filters, and the utilisation of the slag for various public or consumer products such as roads, bridges, parking lots, etc. Other examples of consumer products considered are frying pans, appliances, rooms, offices, office and home furniture, etc. The code can also assess scenarios with controlled products like shield blocks and radwaste containers. The exposure scenarios developed, the pathways considered and exposure parameter used are based on information from technical literature.

The RESRAD-RECYCLE code has a nuclide database of 54 radionuclides. Those with a half-life of less than one year are excluded, except for Mn-54 and Zn-65. The results of the assessments are presented in tabulations of individual, collective and cumulative committed effective doses, based on the scenarios, pathways and radionuclides.

A2.2.2 CERISE

The Code d’Evaluations Radiologiques Individuelles pour les Situations en Entreprise et dans l’Environment (CERISE) was developed by the Institute de Radioprotection et Securité Nucléaire in the framework of European studies on release criteria for very low level radioactive material. The code estimates the dose uptake through different pathways (external exposure, ingestion, inhalation and skin contamination) when an individual is exposed to ionising radiation, expressed as specific, surface or total activity.

The code has a choice of twenty basic built-in scenarios, which are flexible and any one of which can be utilised in part or as a whole. The scenarios can also be combined to reflect the actual situation. The code can be used to study the radiological impact of a specific situation or for calculation of the allowable activity levels for a given dose limit.

The scenarios are structured on the basis of five broad groups of parameters:

- the source term entering the system,
- the parameters diluting the source in the system,
- time related parameters (e.g. duration of exposure),
- parameters related to interaction between the individual and the situation (e.g. exposure geometry, dust distribution, etc.),
- radionuclide associated parameters (e.g. equivalent dose factor, decay, etc.).

The CERISE data bank has currently more than 100 radionuclides with 13 dose factors per nuclide, gamma and beta emission characteristics, and radioactive decay.

Attachment 3

Details of measurements, Phase 1

This attachment gives details of the various measurement campaigns that were carried out. They are described under the following headings:

1. Background measurements at Åkers
   Measurements at Åkers during 'normal' melting of scrap (without Studsvik ingots)
2. Measurements at Åkers during a melt with addition of Studsvik ingots
3. Background measurements during transport of ingots from Studsvik to Åkers
   Background measurements during empty truck drive from Åkers to Studsvik
4. Background measurements at Studsvik new melting facility
   Dose rate measurements at Studsvik during a complete cycle of melting of radioactive scrap (receipt/segmenting/storage/melting/storage)

A3.1 Measurements at Åkers

The background measurements were done during December 19–20 1999.

A3.1.1 BACKGROUND MEASUREMENT

Background dose measurement was performed during 24h with 15 area TLD dosimeters in the scrap yard, melting and machining areas.

Two persons working with scrap and melting had TLD dosimeters for 24 h, with a detection and report limit of 0.1 mSv.

No measurable doses were registered.

Two persons wore air sampling masks during 8 h (air flow 2 l/min and 3µm).

Air sampling Staplex pumps were used, sample volume 700 l.

A3.1.2 ACTIVITY MEASUREMENTS

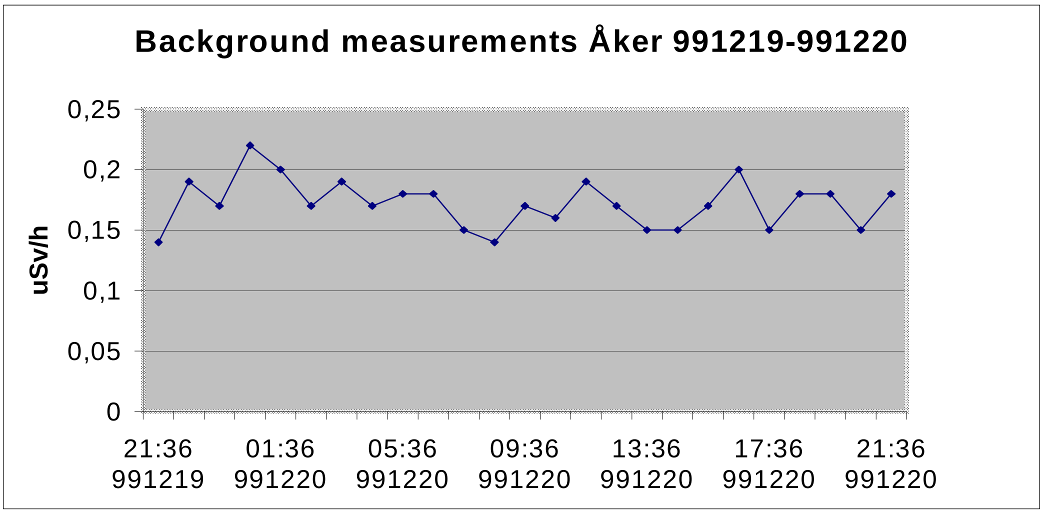
Done with FHT 3 M. Cps equal to nSv/h for Co-60.

The background radiation in the plant and in the scrap yard was 200–300 cps.

Higher radiation levels (700–800 cps) were noted within and outside the coal storage, most probably because the building was built of slag from earlier times (a hundred or more years ago). One point also registered 600 cps at a location behind the wall in the scrap yard.

A3.1.3 DOSE RATE MEASUREMENT

A low dose rate measuring instrument with continuous registration (ESM FH 40G-10) was located adjacent to one of the furnaces for continuous registration of dose rate over 24 h. The background in the hall was 150–200 nSv/h. No peak values over average background were registered during the 24 h period, during which melting of (non-Studsvik) scrap took place.



A3.1.4 RESULTS OF RADIOCHEMICAL SAMPLE MEASUREMENTS.

Traces of radioactivity were found in the dust from furnace ventilation (Ra-226) and from slag samples (Th-232). Both are naturally occurring nuclides.

The following samples were taken and sent for nuclide specific measurements:

1. 1 dust sample from the furnace ventilation
2. 5 samples of additives
3. 1 sample of slag
4. 1 sample of metal
5. 2 air (filter) samples from near the furnace C-oven (700 l)
6. 1 air (filter) sample during pouring of molten steel into the mould (700 l)
7. 2 air (filter) samples from the machining hall (700 l)
8. 2 personal filter samples.

In the following table, the Cs-137 values are shown to indicate the degree of accuracy of measurement.

Sample no	Sample location	Cs-137 (Bg/sample)	Th-232 (Bq/kg)	Ra-226 (Bq/kg)
5	Air filter C-oven melting	< 3.8 E-1		
5	Air filter G-oven melting	< 5.3 E-1		
6	Air filter G-oven pouring	< 3.7 E-1		
7	Air filter roll manufacturing	< 4.8 E-1		
7	Air filter roll manufacturing	< 4.1 E-1		
8	Personal filter no 1	< 5.1 E-1		
8	Personal filter no 2	< 3.4 E-1		
3	Slag		7.8 E0	
1	Dust			4.8 E0
2	Additives FeMo	< 4.6 E 0		
2	Additives Graphite	< 1.9 E 1		
2	Additives FeSi	< 1.8 E 1		
2	Additives Ni	< 8.5 E 0		
2	Additives SiC	< 3.3 E 1		
4	Melt	< 1.2 E 1		

A3.1.5 TLD DOSIMETERS LOCATIONS

Dosimeter	ID-no	Location
509-9513-002	104226	Person dosimeter
509-9513-003	104227	Person dosimeter
509-9513-004	104225	Melting hall C-oven
509-9513-005	104228	Melting hall D-oven
509-9513-006	104221	Melting hall H-oven
509-9513-007	103378	Scrap yard
509-9513-008	104224	Scrap yard
509-9513-009	103369	Scrap yard
509-9513-010	103372	Scrap yard
509-9513-011	103373	Graphite house
509-9513-012	103380	Graphite house
509-9513-013	103377	Big Rolls casting
509-9513-014	103505	Big Rolls casting
509-9513-015	103374	Big Rolls casting
509-9513-016	100257	Big Rolls casting
509-9513-017	102453	Big Rolls casting
509-9513-018	102459	Big Rolls casting

A3.1.6 OCCURRENCE OF RADIOACTIVE NUCLIDES IN THE MOULD PAINT USED AT ÅKERS

Enhanced levels of radioactivity were discovered in the paint used to coat the moulds for the manufacture of rolls during the background measurements made at the melting plant of Åkers (1999-12-20) in connection with the Validation Project.

The paint used at the plant can be either water based or spirit based (product name Steelmol wl) and is delivered in 10 liters sheet metal tins, in which it is stored, while awaiting use.

During the stirring of the paint prior to application as well as during the application of the paint on hot roll moulds, there is a risk for spatter. In addition, there is a risk for the personnel to inhale fumes that may be given off due to heating of the paint during certain phases of the operations.

Sampling

Samples were taken from each type of paint (water/spirit based) as well as from the mixing vessel from which the paint is applied on the moulds. The samples revealed the occurrence of Ra-226 (85 %) and Th-232 (15 %). It was decided, after consultation with the local worker protection organisation, to take air samples. It was also decided then that the personnel involved should undergo whole body monitoring at Studsvik Nuclear (at the HUGO facility).

Results of tests

Paint:	3 500–5 500 Bq/l
Air sampling during painting of moulds:	No detectable alpha or beta activity on filter paper (12 h measurement)
Whole body monitoring: [on HUGO II (Human Body Gamma Outfinder)]	No detectable activity values

Results of radioactivity measurement 1999-12-21

Sample	Bq/l	% Ra-226	% Th-232
Water based paint	3 500	87	13
Spirit based paint	4 600	86	14
‘Concentrate’	5 500	85	15

Samples were taken after stirring.
Quantities: 0.1 l/sample

A3.2 Melting of 7,5 tons of Studsvik ingots at Åkers

It was agreed with Åkers management to melt the Studsvik ingots during a melt cycle from 00-01-31 19.00 hours to 00-02-01 08.00 hours.

A3.2.1 WORK ROUTINE DURING MELTING AT ÅKERS.

Studsvik ingots were transported from storage in the scrap yard and piled in front of the entrance to A-B furnaces (1 man in the truck).

Two persons who were engaged in transport of the ingots to B furnace and loading the furnace were fitted with TLD dosimeters. All workers are at an average distance of 2.5 meters

Melting of a total scrap quantity 24 t (of which 7.5 t was Studsvik ingots) in the B furnace started at 19.00 hours (2 persons to load the furnace).

Pouring into ladle and cutting into blocks from 00-02-01 08.00–11.00 hours (3 persons). A portable air monitor was worn by one person in the shift filter size 3 µm (which is the recommended size by Swedish work safety board, no other size available), who transported the scrap to melt and who loaded the furnace. Measurements were made with low dose detectors in areas where Studsvik ingots were handled.

The melted material was cut into blocks for storage in large steel boxes. Thus the continued manufacturing activities (i.e. casting of rolls, machining, surfaces treatment etc.) were not carried out.

Measurements were made at 3 minutes intervals 00-01-31 20.00 hours to 00-02-01 14.00 hours with FH 40G-10 (low dose instrument with storage function in a PC) in the neighbourhood of B furnace, where all material was melted and poured into the ladles.

Manual air samples were taken with staplex pumps during the loading of the furnace, melting, pouring into the ladles and cutting into blocks.

The average activity concentration on the 7.5 tons were 0,4 Bq/g of Co-60.

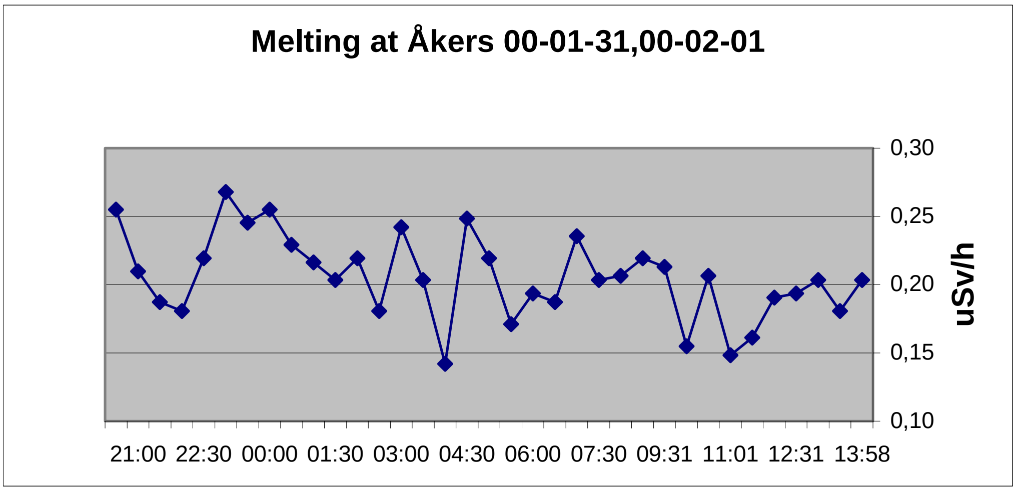
Standard scenarios at Åkers melting facility, for 24 ton of scrap where of 7.5 tons Studsvik scrap.

Operations	Personnel	Time	Distance	Shielding	RESRAD-RECYCLE correspondence
Reception	2	1	2.5 m		Scrap delivery
Sorting/cutting					
Melting					Scrap melting
Loading	2	3	2.5 m		Incl. slag worker
Melting	3	1	2.5 m		
Melting	3	3.3	>5 m		
Pouring	3	2	2.5 m		
Ingot handling	2	2	2.5 m		Ingot delivery
Transfer/storage					Incl. transport

A3.2.2 ONLINE DOSE RATE

Done with ESM FH 40G-10.

Results



A3.2.3 ACTIVITY MEASUREMENTS

Done with FHT 3 M. Cps equal to nSv/h for Co-60.
No manual measurements over background could be measured, i.e. 200–300 cps.

Air filter sampler

Personal pump 2 l/min, total time 8 h = 1 400–2400 l (3 µm)
Air filter 700 l

Slag and dust nuclide specific analysed. All results in Bq/kg

Sample	Co-60	Cs-137	Th-228	Th-232	Ra-226
Melt	1.5 E 2				
Slag		1.4 E 1	2.8 E 2	9.4 E 1	
Dust			2.6 E 1		6.0 E 1
Pers Air filter*		<4.2 E-1			
Air filter*		5.0 E-1			
Air filter*		3.7 E-1			

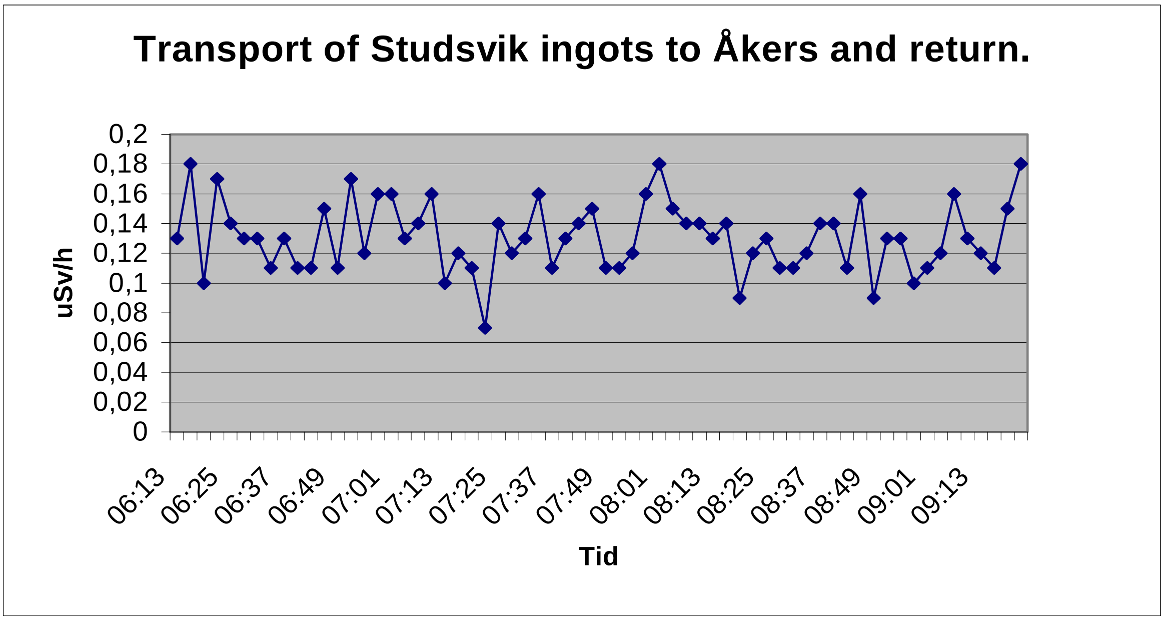
* Bq/sample

A3.3 Transportation between Studsvik and Åkers

The transport was done 00-01-19.
Measurements were done with 31.7 tons of Studsvik ingots, with an average activity of 0.4 Bq/g and without Studsvik ingots to show that no natural occurring nuclides in the soil would add to our dose rate measurements.

The geometry of a pile 5 m long in one layer (0.4 m high) and 0.5 cm of steel shielding was determined.
Dose rate measurements were done with online FH 40G-10.
Unloading took place 07.30–08.00.

Results



A3.4 Measurements done at Studsvik during cutting, melting, storage of contaminated scrap

A3.4.1 GENERAL COMMENTS

When the background measurements were carried out, the melting facility was brand new, except for the cutting hall, which has been to service for 5 years. There were no operation activities carried out, only some last minute construction work. This explains why for example insulation still was in the cutting hall.

A3.4.2 WORK ROUTINE DURING CUTTING AND MELTING OF SCRAP AT STUDSVIK.

Scrap arrives in 20 foot containers which are dose rate controlled and controlled for loose contamination to confirm customer tests.

The container is unloaded into the cutting hall, where sorting and cutting are performed. The cutting hall has a steel floor and suitable ventilation system including spot ventilation for thermal cutting.

Cut scrap is sorted and piled on euro pallets for transport to the melting hall, where the scrap is successively loaded into the furnace.

One melt is approximately 3 500 kg, poured into ladles of each 700 kg. During melting, slag is removed from the surface of the melt and sorted in separate steel buckets.

Samples are taken before pouring into ladle. Ladles are then cooled and ingots taken out for transport to storage for either free release or storage for decay.

Standard scenarios at Studsvik Rad Waste melting facility, for 3 ton of scrap

Operations	Personnel	Time	Distance	Shielding	RESRAD-RECYCLE correspondence
Reception	2	5	0.1-0.5 m		Scrap delivery
Sorting/cutting					
Melting	2	3	0.2-1 m		Scrap melting
Excl. slag workers					Incl. slag worker
Slag workers	3	0.2	0.5-1 m		Included in above
Ingot handling	1	0.2	0.2-1 m		Ingot delivery
Transfer/storage					Incl. transport
Transport	1	2	4 m	0.5 cm steel	

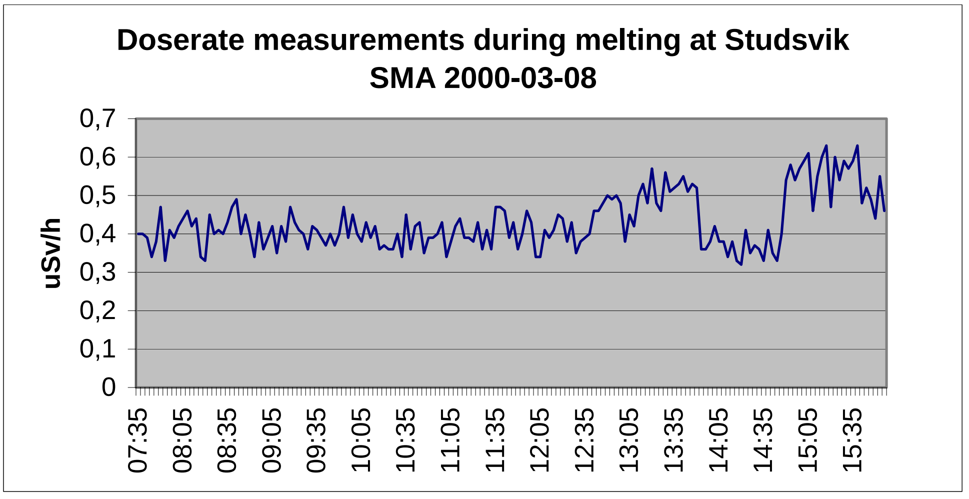
A3.4.3 MEASUREMENTS DURING CUTTING AND MELTING AT STUDSVIK

The measurements were done on 8 March 2000.
On melts no GNS 443–445, total mass of 6 930 kg and a total activity of 5.64 E3 kBq
Slag: approx. 140 kg.

Online dose rate

Done with ESM FH 40G-10.
The instrument was placed at the door between the cutting hall and melting hall.

Results



The above curve represents three melts over a total of 8.5 h.

Activity measurements:

Done with FHT 3 M. Cps equal to nSv/h for Co-60.

There happened to be 1 ingot in the melting hall, as well as slag binding product, stamp mass for the furnace and new insulation. The asphalt was some meters outside the facility.

Place	Background	Melting
General cutting hall	300–350 cps	350–400 cps
General filter room	200–250 cps	250–300 cps
General melting hall	200–250 cps	200–250 cps
Scrap on pallets		500–8000 cps
Slag container at oven		700 cps
Surface dose rate ingot no GNS441		550 cps
Dust container	200–250 cps	450–550 cps
Ingot no 656 activity 170 Bq/kg	250 cps	
Slag binding product	400 cps	
Stamp mass for furnace	700 cps	
New insulation mineral wool	600 cps	
New asphalt 30 cm distance	700 cps	

Air filter sampler

Personal pump 3–5 l/min, total time 8 h = 1 400–2 400 l
cutting < 5.0 E-1 Bq/sample Cs-137
melting < 5.0 E-1 Bq/sample Cs-137

Loose contamination

Smear tests appr. 1 dm^2 and 10 % smearable.
Detection limits Alpha < 0.4 kBq/m^2 and for Beta < 4 kBq/m^2

Place	Alpha kBq/m2	Beta kBq/m2
Scrap 1–12	< 0.4	< 4
Floor melting hall 1–2	< 0.4	< 4
Floor filter room 1–2	< 0.4	< 4

Scrap sample no 9 with 11.6 kBq/m^2 was nuclide specific analysed 1.56 E4 Bq/m^2 of Co-60.

Slag and dust nuclide specific analysed

Sample	Kg	Co-60 Bq/kg	Cs-137 Bq/kg	Tot activity Bq
Slag	Approx. 140	1.5 E2	3.1 E3	4.55 E 5
Dust	< 1	4.7 E2	9.4 E2	

Accumulated personnel dose

TLD no detectable values over background (< 0.1 mSv).

Attachment 4

Details of measurements, Phase 2

A4.1 Background measurements

Background measurements at Studsvik melting plant 01-01-11, before cutting and melting activities with Ringhals fuel racks 01-01-15 and 01-01-16.

Location	Max. dose rate (uSv/h)	General dose rate (uSv/h)
Cutting hall	1.5	0.6–0.8
Melting hall	35	0.8–2.5
Storage area	18	0.8–4.5
Filter room	10	1.0–1.5

Contamination level on floor and in air

Location	Max. contamination level floor (kBq/m^2)	Air contamination (kBq/m^2)
Cutting hall	6	< MDA*
Melting hall	14	< MDA
Storage area	7	3
Filter room	8	3.5

* MDA = minimum detectable activity. All alpha values < MDA.

A4.1.1 DOSE CODES/MAN HOURS/COLLECTIVE DOSE/PERSONNEL

Time schedule for working activities in Studsvik during cutting and melting

Studsvik scenarios Phase 2

Operation	**Dose code**	**No of personnel**	**Man-hours**	**Collective dose (µmanSv)**
1. Transport into shop	610	2	0.3	1
2. Unpacking	611	2	7.4	43
3. Cutting	612	2	19.9	121
4. Melting/Slagging/Pouring	613	2	12.6	32
5. Ingot handling (shielded)	614 a	1	0.7	1
6. Ingot handling (unshielded)	614 b	1	1.5	4
7. Ingot fork driver	615	1	0.2	<1
9. Slag handling	617	1	0.2	2
Total			**42.8**	**204**

A4.1.2 ACTIVITY CONTENT AND WEIGHT

Total nuclide specific activity in Ringhals fuel rack – melted at Studsvik on 2001-01-16

Nuclide	Ingot (MBq)	Cut swarf (MBq)	Slagg (MBq)	Filter dust (MBq)	Total (MBq)
Co-60	518	0.34	8.7	0.02	527
Sb-125	12.2	0.01	0.08	0.0006	12.3
Cs-134	–	–	0.09	–	0.09
Cs-137	–	–	36.3	0.0015	36.3
Eu-154	–	–	0.02	–	0.02
				Total	**575.7 MBq**

	Ingot	Cut swarf	Slagg	Filter Dust
Weight (kg)	3 300	2	55	0.2

A4.1.3 SMEAR AND AIR SAMPLES DURING CUTTING AND MELTING ACTIVITIES IN STUDSVIK 01-01-15–01-01-16.

Smear samples during cutting activities 01-01-15

Location	kBq/m²
Fuel insert position (top of fuel rack)	219
"	783
"	134
Inside pipes (top of fuel racks)	634
"	160
"	658
Fuel support position (bottom of fuel rack)	57
"	44
"	47
Fuel rack sides (outsides of pipes)	41
"	773
"	187
"	2 539*
"	602
"	333
Cutting hall floor during cutting of fuel racks	11
"	4
"	16*

* Samples for nuclide specific measurements.

Smear samples during melting process 01-01-16

Location	kBq/m²
Floor around furnace	35*
"	28
"	33
Furnace edge	301
Floor, general in melting hall	14
"	4
"	3
"	4
Storage hall	16
"	33

Nuclide specific analysis of above marked '*' samples.

Nuclide	Fuel rack (Bq/sample)	Floor furnace (Bq/sample)	Floor cutting hall (Bq/sample)
Co-60	261	28.5	16.5
Cs-137	1.73	0.16	0.17
Sb-125			0.31
	262.7	28.66	16.6

A4.1.4 DOSE RATE INGOTS/SLAG/FILTERDRUM

Surface dose rate on ingots (max.value)	130	μSv/h
Surface dose rate on filter drum	15	μSv/h
Surface dose rate on slag	25	μSv/h
Dose rates on ingots from a distance of 1 meter = max.	7	μSv/h
Dose rates on filter drum and slag from a distance of 1m =	< 2	μSv/h
Smear tests on ingots	< 40	kBq/m^2.

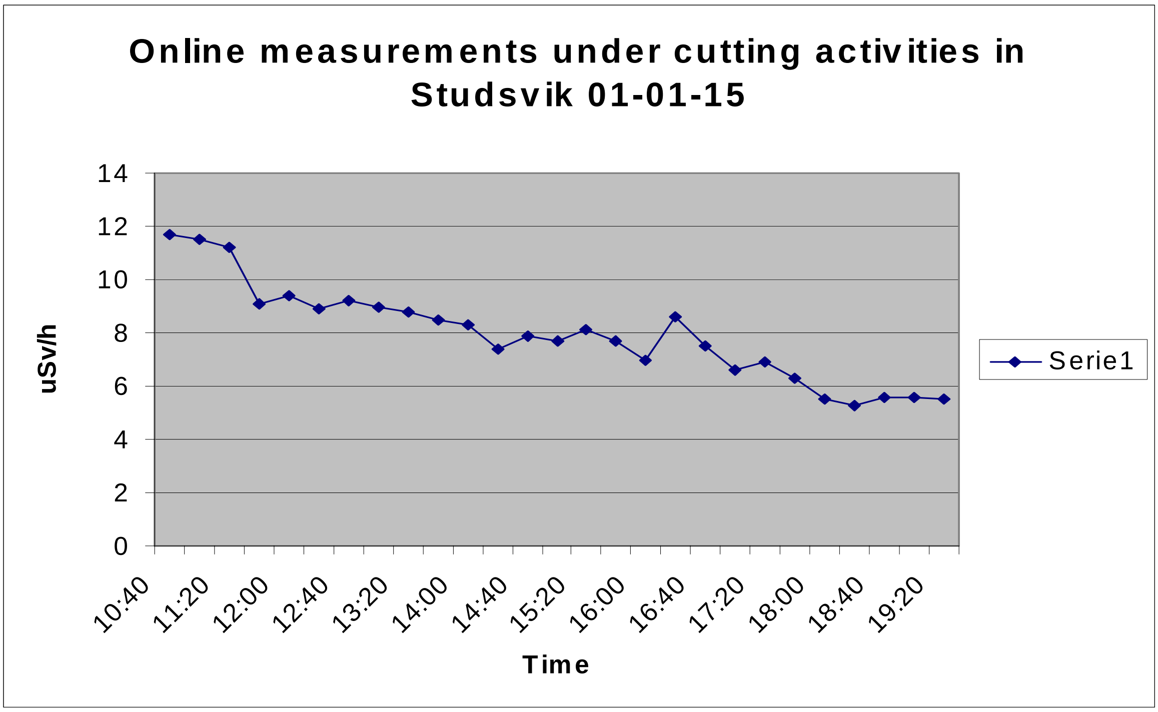
A4.1.5 AIR SAMPLES DURING CUTTING AND MELTING OPERATIONS

Personnel air pump 900 l
Staplex air pump 300 l

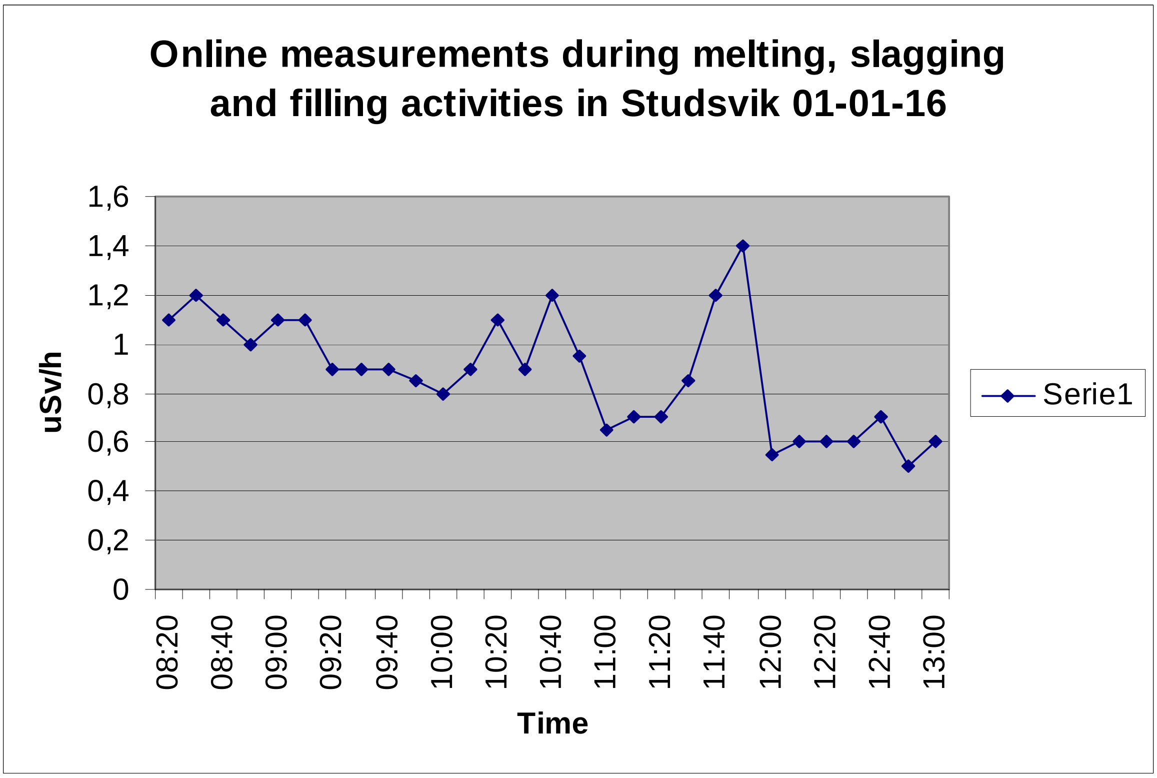
Location	Bq/m^3
Personnel air pump 1 (plasma cutting of fuel racks)	5
Personnel air pump 2 "	4.5
Staplex pump 10 min air sample during plasma cutting	6.5
Personnel air pump 1 (melting, slagging and filling activities)	(40*)
Personnel air pump 2 "	3
Staplex pump 10 min air sample during melting, slagging and filling	8*

Nuclide specific analysis of above marked *samples (Bq/sample)

Nuclide	Personnel air pump (Bq/sample)	Staplex pump (Bq/sample)
Co-60	15.16	1.17
Cs-137	5.5	0.34
Sb-125		
Cr-51	0.56	
Rh-105	10.05	
Bi-214	0.075	
	31.36	**1.51**



Online measurements under cutting activities in Studsvik 01-01-15
14
12
10
8
6
4
2
0
uSv/h
10:40
11:20
12:00
12:40
13:20
14:00
14:40
15:20
16:00
16:40
17:20
18:00
18:40
19:20
Time
Serie1



Online measurements during melting, slagging and filling activities in Studsvik 01-01-16
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
uSv/h
08:20
08:40
09:00
09:20
09:40
10:00
10:20
10:40
11:00
11:20
11:40
12:00
12:20
12:40
13:00
Time
Serie1

A4.1.6 METAL SAMPLES FROM THE 3,0 TON MELT

Nuclide	Sample 1 (Bq/kg)	Sample 2 (Bq/kg)	Cutting debris (Bq/kg)	Slag (Bq/kg)	Filterdust (Bq/kg)
Co-60	1.5 E5	1.6E5	1.7 E5	1.6 E4	8.9 E4
Sb-125	3.5 E3	3.7E3	5.4 E3	1.4 E3	3.3 E3
Cs-134				1.6 E3	
Cs-137				6.6 E5	7.2 E3
Eu-154				3.8 E2	
Weight (g)	389	327	10	78	46

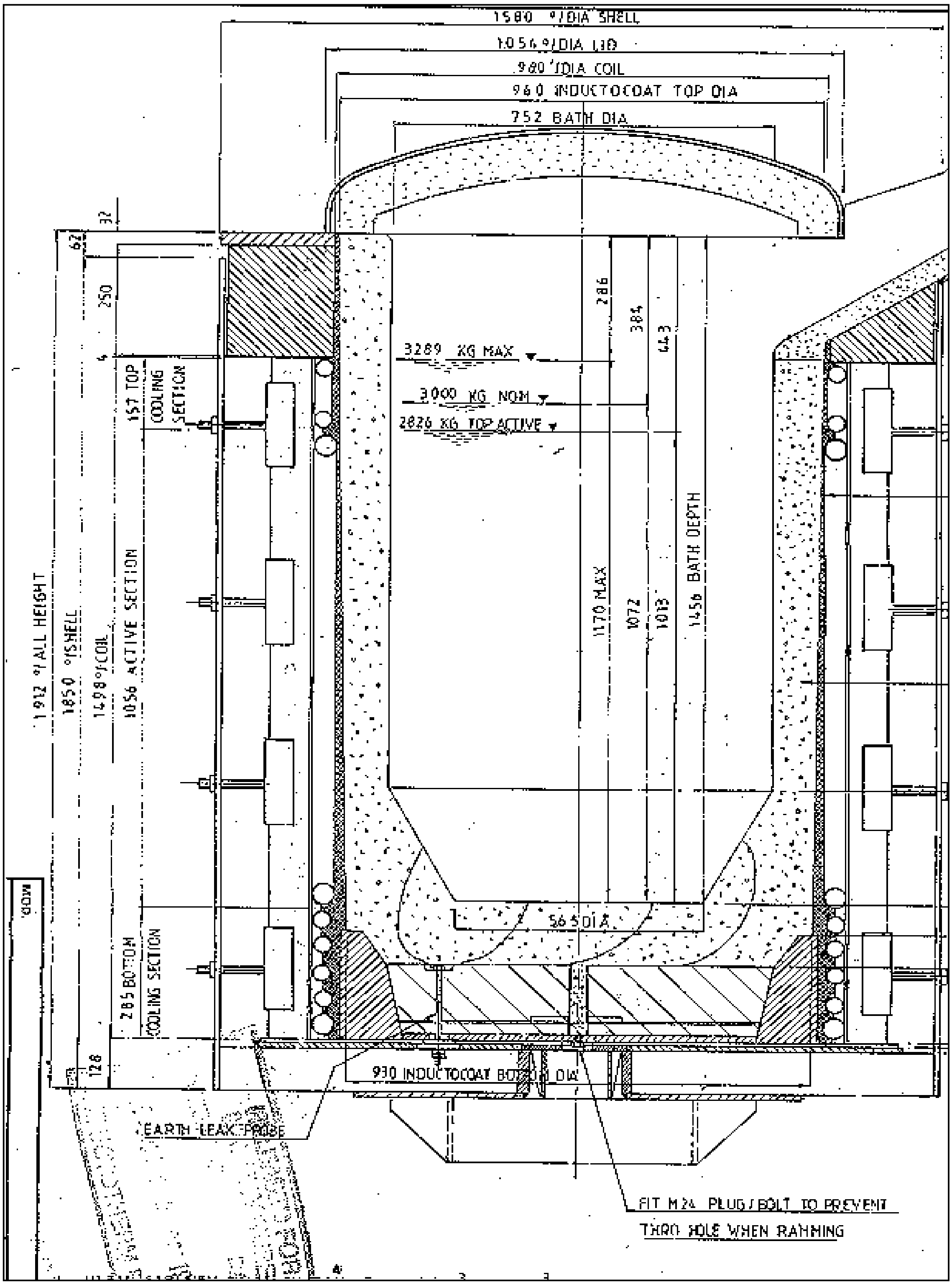
A4.1.7 INSTRUMENTATION

Calibration
ESM/FH 40 G-10
Serial no 11212
Extraction from a full spectrum from 0.001 mSv/h to 100 mSv/h

Dose-equivalent rate	100	30	10	1.0	0.50	0.10	0.05	0.01	0.001
Measured value (mSv/h)	917	28.8	9.5	0.98	0.496	0.096	0.047	0.0098	0.0010

Attachment 5

Sectional view of Studsvik melting furnace



Attachment 6

Some photographs from Phase 2 operations

1. Segmented rack awaiting transfer to furnace.

2. Handling of rack segment.

3. Transport of segmented rack.

4. Feeding rack segment into melter.

5. Feeding rack segment into melter.

6. Moulds for samples from melt.

7. Slagging operation.

8. Slag box.

9.Ingots in moulds.

10. Ingots prepared for transport to storage.

Attachment 7

Technical description of electronic dosimeter RAD-100

RAD-100 *Real Time Dosimeter*

RELIABLE DOSIMETRY RESULTS

The RAD-100 joins the Alnor family of dosimetry products, as the dosimeter for the 90's. It is designed to provide the highest quality real time dosimetry with the Features you need and the Reliability you deserve. Proven environmental and radiological characteristics are maintained in the RAD-100. Alnor's years of experience in the industry have contributed to the outstanding quality of this dosimeter.
Performance is the key.

DOSE AND DOSE RATE

The RAD-100 is the central element in your complete dosimetry system. It's programmable functions supply the user with the possibility to obtain the necessary dose and dose rate data pertinent to the jobs being performed. All displayed data is noticeably visible even in low light conditions.

PROGRAMMABLE FUNCTIONS

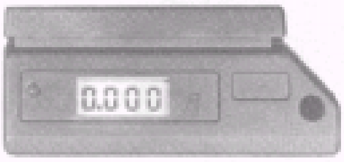
The RAD-100 easily lends itself to simple and error-free use. The ability to program at separate readers allows for several configurations and expands the user's flexibility. Functions include several alarm settings for dose, dose rate, time, and power conditions. The sophistications of this microprocessor controlled unit allow for complete self diagnostic checks and data memories. Mask programmable memory and SMD technology make the RAD-100 truly state-of-the-art.

RUGGED CONSTRUCTION FOR THE MOST DEMANDING ENVIRONMENTS

The design of the RAD-100 challenges true operating conditions. It's aluminum and plastic case is splash proof, high impact resistant, acid and solvent resistant, and easily decontaminated; all important factors in everyday use. Such rugged construction decreases maintenance times and increases productivity.

SYSTEM FLEXIBILITY

- Interface to previous Alnor Readers with minimal upgrade.
- Basic Stand Alone Dosimetry can grow to Integrated Dose Management Systems.
- Infrared communications.
- Primary display, Dose or Dose Rate, user selectable.
- All Alnor Charging Racks can be used.
- Worldwide support by the most experienced dosimetry people: ALNOR.

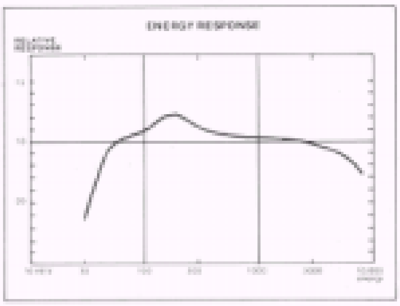


FEATURES

- dose measurement and indication, digital display
- dose rate measurement and indication, digital display
- dose and dose rate alarms, audible and visual
- storage of maximum dose rate value and time of occurence
- storage of total GM tube dose
- continuous operational check, electronics and GM tube
- continuous battery check
- storage of critical data in protected memory
- out of area indication
- battery capacity indication

SPECIFICATIONS

Radiation detected:	gamma and x-rays
Measurement range:	0 mR-1000 R, 0 mR/h-300 R/h (RAD-100R) 0 uSv-1000 mSv, 0-3000 mSv/h (RAD-100S)
Measurement accuracy:	better than ±5% (Cs-137, 28 mR/h)
Energy response:	60 keV – 3 MeV, better than ±30%



(Useful energy response from a few tens of keV to several MeV's.)

Dose rate linearity:	better than ±10% 5mR/h to 300 R/h
Audible alarms:	eight separate: dose, dose rate, dose overflow, dose rate overflow, battery 1, battery 2, timer, error: 80 dBA at a distance of 30 cm
Alarm thresholds:	for dose and dose rate, freely settable in steps of 1 mR-mR/h (uSv-uSv/h) over the whole measurement range Option: 2 sequential dose alarms
Power supply:	NiCd rechargeable battery, life on one charging typically over 100 hours (in background)
Low battery indication:	audible and visual indication when battery capacity is less than 50% (e.g., 8h at a dose rate of 100 mR/h.)
Battery charging:	charging time 16 h with continuous indication of battery state during charging, built in discharge function for periodic battery maintenance
Temperature range:	-10°C – +50°C operational +10°C – +40°C Charging
Humidity range:	max. 90% RH at 20°C
Reader/ dosimeter communication:	using IR transmitter and receiver in bottom of dosimeter
Construction:	high impact waterproof aluminum case
Dimensions:	113 x 66 x 28 mm
Weight:	180 g.

Attachment 8

Benchmarking calculations

At the beginning of the validation project, the default RESRAD-RECYCLE worker scenarios were used to compare dose calculation results from RESRAD-RECYCLE and CERISE. Methodologies employed by the two computer codes were also compared to explain differences in the dose results. Details of this benchmarking exercise are given in the following sections.

A8.1 Scenario descriptions

RESRAD-RECYCLE was specifically designed to analyse radiological exposures associated with reuse or recycling of radioactively contaminated scrap metal. CERISE, on the other hand, was designed for a more general application purpose and can be used to analyse a variety of exposure conditions including but not limited to reuse and recycling. The CERISE code does not include default parameter values. Therefore, the default worker exposure scenarios incorporated into the RESRAD-RECYCLE code were used as the base scenarios for this benchmarking exercise, and the CERISE code was applied to perform dose calculations simulating the exposure conditions considered in the base scenarios.

RESRAD-RECYCLE divides the recycling process into six steps: scrap delivery, scrap melting, ingot delivery, product fabrication, product distribution, and use of the finished product. Representative scenarios for each processing step were developed and incorporated into the code. The first five steps consider worker exposures and the last step considers end-product user exposures. In the benchmarking calculation, attention was focused on the exposures that could occur in a melting facility; therefore, only scenarios associated with the scrap delivery, scrap melting, and ingot delivery steps were considered. The associated scenarios for these three steps are discussed below.

The scrap delivery step involves the transport of scrap metal from the facility generating it to a melting facility. Doses to representative receptors under this step are evaluated for the scrap cutter, scrap loader, and scrap truck driver. The scrap cutter cuts the scrap into smaller pieces for transportation. The scrap loader loads the scrap metal to a transportation vehicle, and the truck driver drives the scrap metal to a melting facility.

The scrap melting step considers the operations in a melting facility. Doses to nine representative receptors are considered under this step: the scrap processor, the smelter yard worker, the smelter loader, the furnace operator, the baghouse processor, the refinery worker, the ingot caster, the small object caster, and the slag worker. The scrap processor performs shredding, cutting, smashing, chopping, bailing, or banding activities to further reduce the volume of scrap pieces for loading to the furnace. The smelter yard worker works in the storage yard of scrap metal and conducts some storage and maintenance activities. The smelter loader loads the scrap to the furnace. The furnace operator operates the furnace and monitors the melting process. The baghouse processor collects dust filters in the baghouse for disposal. The refinery worker conducts and monitors the further refining of the melt product from the furnace. After the melt product is cooled, the ingot caster casts it into large solid objects, and the smaller object caster casts it into smaller objects. Finally, the slag worker removes the slag material for further processing or disposal.

The ingot delivery step considers the delivery of the solid metal products from the melting facility to a downstream manufacturing facility. Representative receptors are evaluated with the ingot loader and the truck driver scenarios.

A8.2 Mass partitioning factors

The term 'mass partitioning factor' refers to the fraction of throughput mass in the melting process that gets into the melting product. An ingot is the main product of the melting process. The mass partitioning of the slag is affected by the mass partitioning of the ingot. Dust and off-gas generated by the furnace are collected in the baghouse. Some of the baghouse contents may be released to the atmosphere through an emission stack.

Mass partitioning factors for steel used in the benchmarking calculation are 90 % for ingot, 10 % for slag, and 1 % for baghouse. These values are both RESRAD-RECYCLE and CERISE default values and were determined by considering the range of the reported values in the literature (CEC 1988; Sappok 1989; Elert and Wilborgh 1992; IAEA 1992; SAIC 1994; S. Cohen and Associates 1995).

A8.3 Radionuclide partitioning factors

During the melting process, radionuclides in the scrap metal could partition to one of the three products: ingot, slag, or dust particles. Radionuclides with low boiling points, such as cesium, typically concentrate in dust particles; those that oxidize easily tend to concentrate in slag. Distribution of radionuclides generally depends on chemical properties of the radionuclides, metallurgical composition of the scrap metal, presence of slag-forming substances added to the melt, melting temperature, and melting method (i.e., the type of furnace).

Default radionuclide partitioning factors in the RESRAD-RECYCLE code were determined on the basis of reviews of literature data, including S. Cohen and Associates (1995), OECD (1994), IAEA (1992), Elert and Wiborgh (1992), Chapuis *et al.* (1987), Hertzler *et al*. (1993), and Nieves *et al*. (1995); communication with researchers in this field; and the developers' best engineering judgment. Default values in the CERISE code were determined on the basis of literature review including OECD (1994), IAEA (1992) and European Communities Commission (CEC 1987, 1993, and1996). For conservative purposes and to account for uncertainties, the sum of the three partitioning factors for some radionuclides may be greater than 1.

Nine radionuclides, Ac-227, Am-241, Co-60, Cs-137, Pu-239, Sr-90, Tc-99, U-238, and Zn-65, were considered in the dose calculations. The RESRAD-RECYCLE default values for these radionuclides were used in the benchmarking calculations and are listed in Table A8.1.

A8.4 Exposure pathways

Three exposure pathways are evaluated by RESRAD-RECYCLE and CERISE external radiation, inhalation, and ingestion. To model external radiation exposure, the radiation source is simulated by a full or half cylinder with dimensions (radius and thickness) representing the source geometry. An external dose conversion factor is calculated for each scenario on the basis of the dimensions of the cylindrical source, the exposure distance, and the density of the source material. Figure A8.1 depicts relative location between the radiation source and the receptor considered in external dose calculation. Attenuation of external radiation can also be considered by specifying the material type, density, and thickness of shielding material located between the radiation source and the exposed workers.

The inhalation pathway considers radiation exposures resulting from inhalation of airborne dust particles. This pathway is evaluated for activities with the potential of causing suspension of source particles. An inhalation rate of 1.2 m^3/h and a respirable fraction of 0.1 were assumed in the benchmarking calculations. A dust loading factor, which is the concentration of airborne dust particles, is used to represent the air quality in the work place. Concentrations of radionuclides in the airborne dust particles are assumed to be the same as those in the source material, with a few exceptions. For the scrap delivery step, the source material for each scenario is the scrap metal itself. For the ingot delivery step, the source material for each scenario is the ingot product. Source material for the scrap melting step can vary for different worker scenarios. For the scrap processor and smelter yard worker scenarios, the source material is the scrap metal. For the ingot caster and small object caster, the source material is the ingot product. For the slag worker, the source material is the slag product. For the baghouse processor, the source material is the dust particles collected in the baghouse filter.

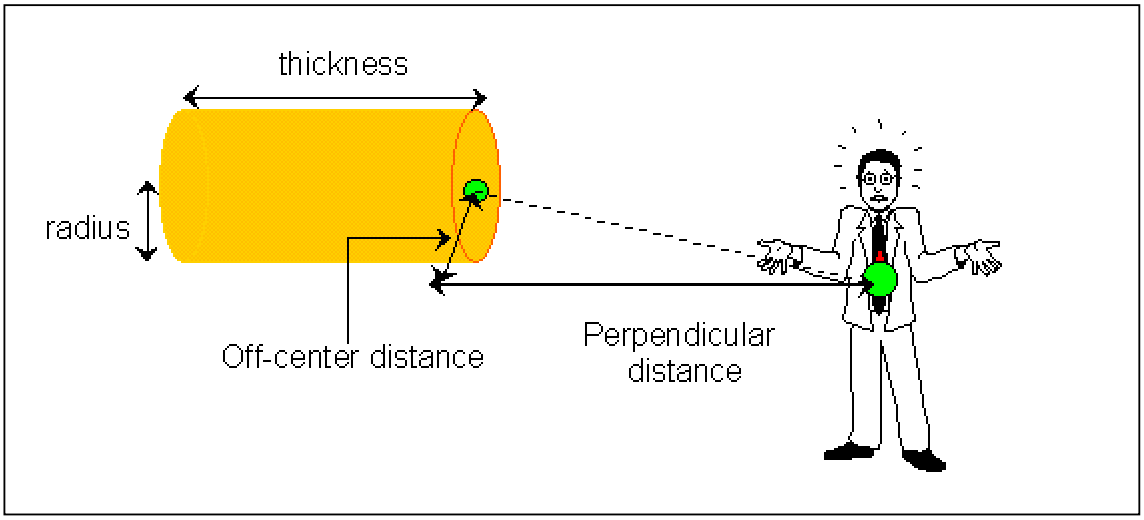


Figure A8.1
Illustration of the relative position between the radiation source and the receptor considered in benchmarking calculations.

For the smelter loader, furnace operator, and refiner worker, dust particles are considered to originate from the melt mixture inside the furnace. However, only volatile components of the mixture would become airborne, and a fraction of them would eventually be collected in the baghouse. Therefore, concentrations of radionuclides in the airborne dust particles are assumed to be the same as those calculated for baghouse dust particles.

For the ingestion pathway, it is assumed that the worker would incidentally ingest the dust particles that deposit on his hands or on the surface of surrounding materials with which his hands come in contact. An ingestion rate of 0.00625 g/h was assumed for the benchmarking calculations. The concentrations of radionuclides in the dust particles are assumed to be the same as those used for the inhalation pathway. In addition to incidental ingestion, RESRAD-RECYCLE considers another exposure component that contributes to the ingestion dose. CERISE, in contrast, does not consider this exposure component. RESRAD-RECYCLE assumes that dust particles that are larger than the respirable size would enter the gastrointestinal tract after they are inhaled. Once these particles are absorbed into the blood stream, they would result in internal radiation exposure, and the resulting radiation doses are attributed to the ingestion pathway.

A8.5 Source geometries and exposure parameters

Scenarios considered in the benchmarking calculations evaluated radiation exposures of workers from handling and processing 30 tons of radioactively contaminated steel. This metal was melted in 10 batches in a furnace with a 3-ton capacity.

In contrast, the default parameter values incorporated into the RESRAD-RECYCLE code were determined on the basis of the assumption that 100 tons of scrap metal would be processed and that the melting facility had a large furnace that could process all that scrap in one batch. For those scenarios considered in the International Atomic Energy Agency (IAEA) report *Application of Exemption Principles to the Recycle and Reuse of Material from Nuclear Facilities* (IAEA 1992), the default values used in RESRAD-RECYCLE were adapted from the values used in that report. For scenarios not considered in the IAEA report, default values for the source dimensions, exposure distances, and exposure durations were developed for RESRAD-RECYCLE on the basis of real-life experiences and the program designers' best judgment, with the intention to provide a reasonably conservative estimate of potential radiation doses.

To perform benchmarking calculations, the default parameter values in RESRAD-RECYCLE were modified to consider a smaller throughput of 30 tons of scrap metal and a smaller furnace size of 3 ton capacity. Table A8.2 lists the source geometry and dimensions, exposure distances and durations, source materials for the external and internal pathways, dust loading factors, and number of workers assumed for the benchmarking calculations.

A8.6 Dose conversion factors

The external radiation model in RESRAD-RECYCLE is based on the dose conversion factors given in the EPA's Federal Guidance Report (FGR) No. 12 (Eckerman and Ryman 1993) and the point kernel method. The external radiation model in CERISE is based on the point kernel method and considers radiation from γ rays for each radionuclide. An external dose conversion factor on the basis of a 1 Bq/g concentration in the source material is calculated for each radionuclide and scenario by both computer codes. The dose conversion factor for a particular radionuclide is then multiplied by the source concentration and exposure duration to obtain the radiation dose for the external radiation pathway.

The internal dose conversion factors used by RESRAD-RECYCLE were obtained from the EPA's Federal Guidance Report No. 11 (Eckerman *et al.* 1988). For some radionuclides, more than one value is listed in the EPA report to account for different chemical forms. In that case, the most conservative value is used as the default value to obtain conservative dose result. The internal dose conversion factors used in CERISE were obtained from European Directive (EURATOM, 1996). For benchmarking calculations, the RESRAD-RECYCLE default inhalation and ingestion dose conversion factors, as listed in Table A8.3, were used by both codes to generate dose results.

A8.7 Dose results and comparison

Dose results from RESRAD-RECYCLE and CERISE are listed and compared in Tables A8.4 to A8.12 for the nine radionuclides considered. Shaded areas in the tables identify results that have greater different between the two codes.

In general, the CERISE results for the inhalation pathway were almost the same as those of RESRAD-RECYCLE, with just a few exceptions. For the ingot caster and small object caster, RESRAD-RECYCLE assumed that the airborne dust particles originated from the ingot product that were handled by the worker. Therefore, in dose calculations, partitioning factors for the ingot product were applied to obtain concentrations of radionuclides in ingots, which then were multiplied by the dust loading factor to get concentrations of radionuclides in the air. The CERISE code, however, multiplied concentrations of radionuclides in scrap metal directly by the dust loading factor to get concentrations of radionuclides in the air. The results for the smelter loader, furnace operator, and refinery worker for Cs-137 and Zn-65 were very different (by a factor 100) between RESRAD-RECYCLE and CERISE. This difference occurred because RESRAD-RECYCLE assumed that radionuclide concentrations in airborne dust particles were the same as those in the baghouse filter dust (see discussions in Section A8.4), while CERISE assumed that they were the same as those in the scrap metal.

Differences were also seen in the ingestion dose results and were orders of magnitude greater for the scrap melting scenarios than for the other scenarios. The differences were caused by two assumptions adopted for dose calculations by the RESRAD-RECYCLE code. The first assumption is that incidental ingestion involves the airborne dust particles that deposit on hands or surfaces of rooms or equipment rather than the source material that is handled by the workers. Therefore, mass and radionuclide partitioning factors applied in dose calculations are consistent with those applied for the inhalation pathway and may be different than those applied for the external radiation pathway (see discussions in Section A8.4 and information in Table A8.2). In the CERISE calculations, incidental ingestion involves deposition of source material that is handled by the workers; therefore, mass partitioning factors applied for the ingestion pathway are the same as those applied for the external radiation pathway. The second assumption of interest used by RESRAD-RECYCLE is that airborne dust particles greater than the respirable size would enter the GI tract of a human body once they were inhaled through the nostrils. Radionuclides attached to these dust particles would cause radiation exposures, and they are attributed to the ingestion pathway. In the CERISE calculations, only incidental ingestion is considered. As a result, the ingestion doses calculated by RESRAD-RECYCLE are greater than those calculated by CERISE.

External radiation doses calculated by RESRAD-RECYCLE and CERISE were different. This difference was caused by differences in the external radiation models. RESRAD-RECYCLE results are much smaller than those of CERISE for the smelter yard worker, smelter loader, furnace operator, and refining worker. The large differences for these scenarios can be explained by the RESRAD-RECYCLE assumption of the presence of a concrete shielding material (with a thickness of 30 cm and a density of 2.8 g/cm^3 to represent the wall of the furnace). No shielding was assumed in CERISE calculations.

Table A8.13 shows that when there is no shielding, the results from RESRAD-RECYCLE and CERISE code are comparable, except for beta emitters where RESRAD-RECYCLE results are more conservative. With shielding, the dose results vary depending on the attenuation due to shielding from different gamma energies. The RESRAD-RECYCLE external exposure model uses FGR-12 dose conversion factors for infinite geometry and applies correction for source dimensions, receptor distance, and shielding (depth factor, cover factor, shape factor, and area factor) which depend on the associated radiation energies. Table A8.14 provides the DCFs for external exposure used and the photon energies (all associated photon energies from a radionuclide were collapsed into a maximum of four groups) with their corresponding fractions used in the dose calculations. The photon energies and yields were obtained by condensing ICRP 38 photon spectra. This table also shows the Smelter yard worker scenario dose ratio with no shielding and with shielding from RESRAD-RECYCLE code. As expected, the attenuation from Co-60 (maximum photon energy) is least, followed by Zn-65, U-238, Cs-137, Ac-227, Pu-239, Tc-99, and maximum attenuation for Am-241 (lowest gamma energy). The dose from Ac-227 is attenuated less compared to Am-241 because of the differences in the associated photon energies.

Table A8.1 *Radionuclide partitioning factors used in benchmarking calculations.*

Radionuclides	Ingot (%)	Baghouse (%)	Slag (%)	Total (%)
Ac-227	0	1	99	100
Am-241	0	1	99	100
Co-60	99	1	0	100
Cs-137	0	97	3	100
Pu-239	0	1	99	100
Sr-90	0	1	99	100
Tc-99	99	1	0	100
U-238	0	1	99	100
Zn-65	1	99	0	100

Table A8.2 *Radiation source geometry and exposure parameter used in benchmarking calculations.*

Recycle step	Worker scenario	Source geometry	Mass (t)	Density (g/cm³)	Thickness (cm)	Radius (cm)	Distance (cm)	Time (h)	Source material[a] for the external pathway	Source material[a] for the internal pathways	Dust loading (g/m³)	Number of workers
Scrap delivery	Scrap cutter	1 half cylinder	0.5	3.93	90	30	200	3.6	Scrap	Scrap	5E-4	3
	Scrap loader	1 half cylinder	15	3.93	213	107	400	2	Scrap	Scrap	5E-4	2
	Scrap truck driver	1 half cylinder	15	3.93	818	55	200	4	Scrap	None	0	2
Scrap melting	Scrap processor	1 half cylinder	0.5	5.90	60	30	200	3.6	Scrap	Scrap	1E-4	3
	Smelter yard worker[b]	1 half cylinder	3	5.90	109	54	1 000	24	Scrap	Scrap	3E-3	10
	Smelter loader[b]	1 half cylinder	3	5.90	109	54	400	1.2	Scrap	Baghouse filter	3E-3	3
	Furnace operator[b]	1 full cylinder	3	7.86	79	40	300	1.5	Scrap	Baghouse filter	3E-3	3
	Baghouse processor	1 full cylinder	0.5	2.00	79	32	200	0.3	Baghouse filter	Baghouse filter	3E-3	1
	Refinery worker[b]	1 full cylinder	3	7.86	73	41	300	1.5	Ingot	Baghouse filter	3E-3	3
	Ingot caster	1 full cylinder	0.5	7.86	37	24	150	0.75	Ingot	Ingot	1E-3	2
	Small object caster	1 full cylinder	0.1	7.86	1	63.5	100	15	Ingot	Ingot	1E-3	2
	Slag worker	1 half cylinder	3	2.7	30	153	150	7.5	Slag	Slag	3E-3	1
Ingot delivery	Ingot loader	1 half cylinder	13.5	7.86	65	130	400	0.6	Ingot	None	0	2
	Ingot truck driver	1 full cylinder	13.5	7.86	175	56	200	5	Ingot	None	0	2

[a] Radionuclide concentrations in the specified materials were used in the pathway calculations for the various steps of the process.

[b] A concrete shielding with a density of 2.8 g/cm³ and a thickness of 30 cm was assumed for the calculation of external dose by RESRAD-RECYCLE. CERISE did not assume the existence of shielding material in its dose calculations.

Table A8.3 *Internal dose conversion factors used in benchmarking calculations.*

Radionuclides	Inhalation (Sv/Bq)	Ingestion (Sv/Bq)
Ac-227	4.00E-6	1.82E-3
Am-241	9.84E-7	1.20E-4
Co-60	7.28E-9	5.91E-8
Cs-137	1.35E-8	8.63E-9
Pu-239	9.56E-7	1.16E-4
Sr-90	4.13E-8	3.54E-7
Tc-99	3.95E-10	2.25E-9
U-238	7.27E-8	3.20E-5
Zn-65	3.90E-9	5.50E-9

Table A8.4 *Benchmarking calculation results for Ac-227*[a].

Recycle step	Worker scenario	Ingestion dose (μSv)		Inhalation dose (μSv)		External dose (μSv)	
		RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Scrap delivery	Scrap cutter	9.62E-2	8.86E-2	3.87E-1	3.87E-1	8.58E-4	1.05E-3
	Scrap loader	5.35E-2	4.92E-2	2.15E-1	2.15E-1	1.48E-3	1.82E-3
	Scrap truck driver	0	0	0	0	3.09E-3	3.91E-3
Scrap melting	Scrap processor	9.01E-2	8.85E-2	7.74E-2	7.74E-2	8.68E-4	1.05E-3
	Smelter yard worker	8.97E-2	5.90E-1	1.55E1	1.55E1	1.70E-7	9.23E-4
	Smelter loader	4.48E-2	2.95E-2	7.74E-1	7.74E-1	5.01E-8	2.85E-4
	Furnace operator	5.60E-2	3.68E-8	9.67E-1	9.67E-1	1.18E-7	6.95E-4
	Baghouse processor	1.12E-2	7.39E-3	1.93E-1	1.93E-1	1.57E-4	1.99E-4
	Refinery worker	5.60E-2	3.68E-2	9.67E-1	9.67E-1	0	0
	Ingot caster	0	1.84E-2	0	1.61E-1	0	0
	Small objects caster	0	3.68E-1	0	3.22E+0	0	0
	Slag worker	2.77E+0	1.83E+0	4.79E+1	4.79E+1	4.84E-1	7.46E-2
Ingot delivery	Ingot loader	0	0	0	0	0	0
	Ingot truck driver	0	0	0	0	0	0

[a] Shading identifies areas of larger differences between the results of the two models.

Table A8.5 *Benchmarking calculation results for Am-241[a].*

Recycle Step	Worker Scenario	Ingestion Dose (µSv)		Inhalation Dose (µSv)		External Dose (µSv)	
		RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Scrap delivery	Scrap cutter	2.40E-2	2.21E-6	2.59E-2	2.59E-2	2.46E-6	4.16E-6
	Scrap loader	1.34E-2	1.23E-6	1.44E-2	1.44E-2	4.02E-6	7.22E-6
	Scrap truck driver	0	0	0	0	8.86E-6	1.52E-5
Scrap melting	Scrap processor	2.25E-2	2.21E-2	5.18E-3	5.18E-3	2.47E-6	4.16E-6
	Smelter yard worker	2.24E-1	1.41E-1	1.04E+0	1.04E+0	1.43E-18	3.65E-6
	Smelter loader	1.12E-2	7.37E-3	5.18E-2	5.18E-2	4.29E-19	1.13E-6
	Furnace operator	1.40E-2	9.20E-3	6.47E-2	6.48E-2	1.03E-18	2.75E-6
	Baghouse processor	2.80E-3	1.85E-3	1.29E-2	1.30E-2	4.65E-7	7.87E-7
	Refinery worker	1.40E-2	9.20E-3	6.47E-2	6.48E-2	0	0
	Ingot caster	0	4.61E-3	0	1.08E-2	0	0
	Small objects caster	0	9.20E-2	0	2.16E-1	0	0
	Slag worker	6.93E-1	4.58E-1	3.21E+0	3.21E+0	1.39E-3	2.76E-3
Ingot delivery	Ingot loader	0	0	0	0	0	0
	Ingot truck driver	0	0	0	0	0	0

[a] Shading identifies areas of larger differences between the results of the two models.

Table A8.6 *Benchmarking calculation results for Co-60[a].*

Recycle Step	Worker Scenario	Ingestion Dose (µSv)		Inhalation Dose (µSv)		External Dose (µSv)	
		RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Scrap delivery	Scrap cutter	1.67E-4	1.53E-4	1.20E-5	1.20E-5	8.53E-3	6.85E-3
	Scrap loader	9.26E-5	8.53E-5	6.65E-6	6.65E-6	1.50E-2	1.19E-2
	Scrap truck driver	0	0	0	0	3.08E-2	2.68E-2
Scrap melting	Scrap processor	1.56E-4	1.53E-4	2.39E-6	2.39E-6	8.72E-3	6.85E-3
	Smelter yard worker	1.55E-3	1.02E-3	4.78E-4	4.78E-4	5.74E-5	6.02E-3
	Smelter loader	7.77E-5	5.11E-5	2.39E-5	2.39E-5	1.65E-5	1.86E-3
	Furnace operator	9.71E-5	6.38E-5	2.99E-5	2.99E-5	3.88E-5	4.53E-3
	Baghouse processor	1.94E-5	1.28E-6	5.98E-6	5.98E-6	1.52E-3	1.30E-3
	Refinery worker	9.71E-5	6.38E-5	2.99E-5	2.99E-5	4.47E-5	5.22E-3
	Ingot caster	4.13E-5	3.20E-5	5.48E-6	4.98E-6	4.55E-3	3.56E-3
	Small objects caster	8.25E-4	6.38E-4	1.10E-4	9.97E-5	2.88E-1	3.24E-1
	Slag worker	0	0	0	0	0	0
Ingot delivery	Ingot loader	0	0	0	0	7.25E-3	5.69E-3
	Ingot truck driver	0	0	0	0	9.04E-2	7.13E-2

[a] Shading identifies areas of larger differences between the results of the two models.

Table A8.7 Benchmarking calculation results for Cs-137[a].

Recycle Step	Worker Scenario	Ingestion Dose (μSv)		Inhalation Dose (μSv)		External Dose (μSv)	
		RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Scrap delivery	Scrap cutter	3.26E-4	3.00E-4	1.84E-6	1.84E-6	1.92E-3	1.34E-3
	Scrap loader	1.81E-4	1.67E-4	1.02E-6	1.02E-6	3.35E-3	2.32E-3
	Scrap truck driver	0	0	0	0	6.93E-3	4.95E-3
Scrap melting	Scrap processor	3.05E-4	3.00E-4	3.69E-7	3.69E-7	1.96E-3	1.34E-3
	Smelter yard worker	3.04E-3	2.00E-3	7.37E-5	7.37E-5	3.15E-6	1.17E-3
	Smelter loader	1.47E-2	1.00E-4	3.57E-4	3.69E-6	9.13E-7	3.62E-4
	Furnace operator	1.84E-2	1.25E-4	4.47E-4	4.61E-6	2.15E-6	8.93E-4
	Baghouse processor	3.69E-3	2.43E-3	8.94E-5	8.94E-5	3.36E-2	2.45E-2
	Refinery worker	1.84E-2	1.25E-4	4.47E-4	4.61E-6	0	0
	Ingot caster	0	6.25E-5	0	7.68E-7	0	0
	Small objects caster	0	1.25E-3	0	1.54E-5	0	0
	Slag worker	2.85E-4	1.88E-4	6.91E-6	6.91E-6	3.31E-2	2.69E-2
Ingot delivery	Ingot loader	0	0	0	0	0	0
	Ingot truck driver	0	0	0	0	0	0

[a] Shading identifies areas of larger differences between the results of the two models.

Table A8.8 Benchmarking calculation results for Pu-239[a].

Recycle Step	Worker Scenario	Ingestion Dose (μSv)		Inhalation Dose (μSv)		External Dose (μSv)	
		RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Scrap delivery	Scrap cutter	2.34E-2	2.15E-2	2.51E-2	2.51E-2	7.32E-8	5.0E-8
	Scrap loader	1.30E-2	1.19E-2	1.39E-2	1.39E-2	1.22E-7	8.67E-8
	Scrap truck driver	0	0	0	0	2.63E-7	1.83E-7
Scrap melting	Scrap processor	2.19E-2	2.15E-2	5.01E-3	5.01E-3	7.37E-8	5.0E-8
	Smelter yard worker	2.18E-1	1.43E-1	1.0E+0	1.00E+0	1.18E-12	4.39E-8
	Smelter loader	1.09E-2	7.16E-3	5.01E-2	5.01E-2	3.53E-13	1.35E-8
	Furnace operator	1.36E-2	8.94E-3	6.26E-2	6.26E-2	8.37E-13	3.30E-8
	Baghouse processor	2.72E-3	1.79E-3	1.25E-2	1.25E-2	1.36E-8	9.45E-9
	Refinery worker	1.36E-2	8.94E-3	6.26E-2	6.26E-2	0	0
	Ingot caster	0	4.48E-3	0	1.04E-2	0	0
	Small objects caster	0	8.94E-2	0	2.09E-1	0	0
	Slag worker	6.74E-1	4.45E-1	3.10E+0	3.10E+0	4.13E-5	3.32E-5
Ingot delivery	Ingot loader	0	0	0	0	0	0
	Ingot truck driver	0	0	0	0	0	0

[a] Shading identifies areas of larger differences between the results of the two models.

Table A8.9 *Benchmarking Calculation Results for Sr-90*[a].

Recycle Step	Worker Scenario	Ingestion Dose (µSv)		Inhalation Dose (µSv)		External Dose (µSv)	
		RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Scrap delivery	Scrap cutter	9.98E-4	9.18E-4	7.56E-5	7.55E-5	1.84E-6	9.16E-7
	Scrap loader	5.54E-4	5.10E-4	4.20E-5	4.20E-5	2.20E-6	1.57E-6
	Scrap truck driver	0	0	0	0	6.59E-6	3.40E-6
Scrap melting	Scrap processor	9.34E-4	9.17E-4	1.51E-5	1.51E-5	1.84E-6	9.16E-7
	Smelter yard worker	9.30E-3	6.11E-3	3.02E-3	3.02E-3	3.42E-7	8.05E-7
	Smelter loader	4.65E-4	3.06E-4	1.51E-4	1.51E-4	1.71E-8	2.48E-7
	Furnace operator	5.81E-4	3.82E-4	1.89E-4	1.89E-4	4.27E-8	6.05E-7
	Baghouse processor	1.16E-4	7.65E-5	3.78E-5	3.78E-5	3.48E-7	1.73E-7
	Refinery worker	5.81E-4	3.82E-4	1.89E-4	1.89E-4	0	0
	Ingot caster	0	1.91E-4	0	3.15E-5	0	0
	Small objects caster	0	3.82E-3	0	6.29E-4	0	0
	Slag worker	2.88E-2	1.90E-2	9.35E-3	9.35E-3	1.07E-3	6.09E-4
Ingot delivery	Ingot loader	0	0	0	0	0	0
	Ingot truck driver	0	0	0	0	0	0

[a] Shading identifies areas of larger differences between the results of the two models.

Table A8.10 *Benchmarking calculation results for Tc-99*[a].

Recycle Step	Worker Scenario	Ingestion Dose (µSv)		Inhalation Dose (µSv)		External Dose (µSv)	
		RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Scrap delivery	Scrap cutter	9.66E-6	8.89E-6	4.86E-7	4.86E-7	1.17E-8	2.39E-10
	Scrap loader	5.36E-6	4.94E-6	2.70E-7	2.70E-7	1.96E-8	4.15E-10
	Scrap truck driver	0	0	0	0	4.22E-8	8.76E-10
Scrap melting	Scrap processor	9.04E-6	8.88E-6	9.72E-8	9.72E-8	1.18E-8	2.39E-10
	Smelter yard worker	9.00E-5	5.92E-5	1.94E-5	1.94E-5	1.10E-16	2.10E-10
	Smelter loader	4.50E-6	2.96E-6	9.72E-7	9.72E-7	3.31E-17	6.48E-11
	Furnace operator	5.62E-6	3.69E-6	1.21E-6	1.21E-6	7.89E-17	1.58E-10
	Baghouse processor	1.12E-6	7.41E-7	2.43E-7	2.47E-7	2.21E-9	4.53E-11
	Refinery worker	5.62E-6	3.69E-6	1.21E-6	1.21E-6	9.09E-17	1.82E-10
	Ingot caster	2.39E-6	1.85E-6	2.23E-7	2.03E-7	6.17E-9	1.24E-10
	Small objects caster	4.78E-5	3.69E-5	4.45E-6	4.05E-6	1.68E-6	3.03E-8
	Slag worker	0	0	0	0	0	0
Ingot delivery	Ingot loader		0	0	0	9.34E-9	1.99E-10
	Ingot truck driver	0	0	0	0	1.21E-7	2.49E-7

[a] Shading identifies areas of larger differences between the results of the two models.

Table A8.11 Benchmarking calculation results for U-238[a].

Recycle Step	Worker Scenario	Ingestion Dose (μSv)		Inhalation Dose (μSv)		External Dose (μSv)	
		RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Scrap delivery	Scrap cutter	1.78E-3	1.64E-3	6.91E-3	6.91E-3	6.11E-5	4.97E-5
	Scrap loader	9.87E-4	9.09E-4	3.84E-3	3.84E-3	1.07E-4	8.62E-5
	Scrap truck driver	0	0	0	0	2.20E-4	1.82E-4
Scrap melting	Scrap processor	1.66E-3	1.63E-3	1.38E-3	1.38E-3	6.23E-5	4.97E-5
	Smelter yard worker	1.66E-2	1.09E-2	2.76E-1	2.76E-1	1.59E-7	4.36E-5
	Smelter loader	8.28E-4	5.45E-4	1.38E-2	1.38E-2	4.61E-8	1.35E-5
	Furnace operator	1.03E-3	6.80E-4	1.73E-2	1.73E-2	1.08E-7	3.28E-5
	Baghouse processor	2.07E-4	1.36E-4	3.46E-3	3.46E-3	1.10E-5	9.39E-6
	Refinery worker	1.03E-3	6.80E-4	1.73E-2	1.73E-2	0	0
	Ingot caster	0	3.41E-4	0	2.88E-3	0	0
	Small objects caster	0	6.80E-3	0	5.76E-2	0	0
	Slag worker	5.12E-2	3.38E-3	8.55E-1	8.55E-1	3.49E-2	3.99E-2
Ingot delivery	Ingot loader	0	0	0	0	0	0
	Ingot truck driver	0	0	0	0	0	0

[a] Shading identifies areas of larger differences between the results of the two models.

Table A8.12 Benchmarking calculation results for Zn-65[a].

Recycle Step	Worker Scenario	Ingestion Dose (μSv)		Inhalation Dose (μSv)		External Dose (μSv)	
		RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE	RESRAD-RECYCLE	CERISE
Scrap delivery	Scrap cutter	5.93E-5	5.46E-5	7.41E-7	7.39E-6	1.31E-3	1.02E-3
	Scrap loader	3.30E-5	3.03E-5	4.11E-7	4.11E-7	2.29E-3	1.77E-3
	Scrap truck driver	0	0	0	0	4.71E-3	6.01E-3
Scrap melting	Scrap processor	5.56E-5	5.46E-5	1.48E-7	1.48E-7	1.33E-3	1.02E-3
	Smelter yard worker	5.53E-4	3.64E-4	2.96E-5	2.96E-5	5.55E-6	8.98E-4
	Smelter loader	2.74E-3	1.82E-5	1.47E-4	1.48E-6	1.60E-6	2.77E-4
	Furnace operator	3.42E-3	2.27E-5	1.83E-4	1.85E-6	3.75E-6	6.75E-4
	Baghouse processor	6.84E-4	4.51E-4	3.67E-5	3.66E-5	2.31E-2	1.91E-2
	Refinery worker	3.42E-3	2.27E-5	1.83E-4	1.85E-6	4.38E-8	7.87E-6
	Ingot caster	1.48E-7	1.14E-5	3.43E-9	3.08E-7	7.02E-6	5.36E-6
	Small objects caster	2.97E-6	2.27E-4	6.86E-8	6.12E-6	4.66E-4	5.31E-4
	Slag worker	0	0	0	0	0	0
Ingot delivery	Ingot loader	0	0	0	0	1.12E-5	8.58E-6
	Ingot truck driver	0	0	0	0	1.40E-4	1.07E-4

[a] Shading identifies areas of larger differences between the results of the two models.

Table A8.13 Selected external pathway dose (uSv per Bq/g) with RESRAD-RECYCLE and CERISE codes.

		RESRAD-RECYCLE		CERISE
Radionuclides	**Recycle step**	**with shielding**	**without shielding**	**without shielding**
Ac-227+D	Smelter yard worker	1.70E-7	7.47E-4	9.23E-4
	Smelter loader	5.01E-8	2.36E-4	2.85E-4
	Furnace operator	1.18E-7	5.78E-4	6.95E-4
	Refinery worker	0	0	0
Am-241	Smelter yard worker	1.43E-18	1.82E-6	3.65E-6
	Smelter loader	4.29E-19	6.40E-7	1.13E-6
	Furnace operator	1.03E-18	1.60E-6	2.75E-6
	Refinery worker	0	0	0
Co-60	Smelter yard worker	5.74E-5	7.72E-3	6.02E-3
	Smelter loader	1.65E-5	2.40E-3	1.86E-3
	Furnace operator	3.88E-5	5.87E-3	4.53E-3
	Refinery worker	4.47E-5	6.78E-3	5.22E-3
Cs-137	Smelter yard worker	3.15E-6	1.71E-3	1.17E-3
	Smelter loader	9.13E-7	5.36E-4	3.62E-4
	Furnace operator	2.15E-6	1.31E-3	8.93E-4
	Refinery worker	0	0	0
Pu-239	Smelter yard worker	1.18E-12	5.98E-8	4.39E-8
	Smelter loader	3.53E-13	1.95E-8	1.35E-8
	Furnace operator	8.37E-13	4.82E-8	3.30E-8
	Refinery worker	0	0	0
Tc-99	Smelter yard worker	1.10E-16	9.34E-9	2.10E-10
	Smelter loader	3.31E-17	3.12E-9	6.48E-11
	Furnace operator	7.89E-17	7.71E-9	1.58E-10
	Refinery worker	9.09E-17	8.90E-9	1.82E-10
U-238+D	Smelter yard worker	1.59E-7	5.46E-5	4.36E-5
	Smelter loader	4.61E-8	1.71E-5	1.35E-5
	Furnace operator	1.08E-7	4.18E-5	3.28E-5
	Refinery worker	0	0	0
Zn-65	Smelter yard worker	5.55E-6	1.18E-3	8.98E-4
	Smelter loader	1.60E-6	3.66E-4	2.77E-4
	Furnace operator	3.75E-6	8.97E-4	6.75E-4
	Refinery worker	4.38E-8	1.05E-5	7.87E-6

+D indicates that the dose contribution of the progeny radionuclides with half-lives less than 6 months is included in the dose calculations of their parent radionuclide.

Table A8.14 Dose ratios with and without shielding and photon energies and fractions.

Radio-nuclide	**Smelter yard worker (no shield /shield)**	**DCF mrem/yr per pCi/g**	**Collapsed photon energies (keV)**				**Associated photon fractions (%)**			
Ac-227+D	4.4E3	2.01	14.0	94.2	330	–	64.1	90.6	86	–
Am-241	1.3E12	4.37E-2	16.8	59.5	–	–	66.5	35.7	–	–
Pu-239	5.1E5	2.95E-4	<1	16.1	48.8	187	99.9	4.17	0.03	0.02
U-238+D	340	1.37E-1	15.5	82.7	915	–	19.1	10.2	1.5	–
Tc-99(*)	8.5E7	1.26E-4	101	–	–	–	0.15	–	–	–
Co-60	130	16.2	1 250	–	–	–	200	–	–	–
Cs-137	540	3.41	32.1	662	–	–	5.72	85	–	–
Zn-65	210	3.70	8.04	1 080	–	–	34.1	53.6	–	–

(*) For beta emitters energy considered is the average beta energy and the fraction is the fraction of the beta energy converted to photons to approximate the bremsstrahlung contribution to the external dose.

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