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RADIATION IMPACT DURING THE DECONTAMINATION BY MELTING OF RADIOACTIVE SCRAP METAL ARISEN FROM THE DECOMMISSIONING OF NUCLEAR POWER PLANTS

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Decontamination of radioactive scrap metal by melting is a prospective technology to reduce the amount of metallic radioactive waste. Melting technology provides a particular advantage of homogenising a number of radionuclides in the ingots and concentrating other radionuclides in the slag and dust filter resulting from the melting process, thus decontaminating the primary material. The presented paper also deals with the evaluation of exposure of the workers during melting of radioactive scrap metal. According to the obtained results, the effective doses absorbed by workers during the melting meets the legislatively given limit 20 mSv per annum.

K e y w o r d s: decommissioning, radioactive scrap metal, metal melting

1 INTRODUCTION

At present there are more than 400 nuclear power plants (NPP) and many other nuclear installations (NI) in operation worldwide. However, all technological equipment is limited by its lifetime and after its expiration the nuclear power plant (or NI) has to be decommissioned and dismantled. It is estimated by the OECDs Nuclear Energy Agency that about 400 commercial nuclear power plants will be decommissioned till 2050, which may result in more than 5 million tonnes of scrap metal suitable for recycling. Considering all other types of NI that will also be decommissioned, the amount of scrap metal arisen from decommissioning in the coming decades is estimated to be about 30 million tonnes [1].

The large amount of slightly radioactive scrap metal arising from decommissioning of NI may present notable problems in radioactive waste (RAW) management. Currently operating waste disposal facilities cannot accommodate such large volumes of metal waste (for reasons of costs or because of public opposition to expansion of available waste capacity or to the sitting of new disposal capacities) and therefore decontamination and recycling is a suitable way to reduce significant amounts of waste [1-3].

2 DECONTAMINATION BY MELTING

A particularly advantageous consequence of melting is its decontamination effect on ^{137}Cs, a volatile element that has a half-life of 30 years. During melting, ^{137}Cs accumulates in the dust collected by ventilation filters and is removed. The dominant remaining nuclide in the ingots (for most reactor scrap) is ^{60}Co. This element has a half-life of only 5.3 years. Other remaining nuclides have even shorter half-lives. Consequently, ingots with reasonably low-activity concentrations may be stored for release in a foreseeable future [4,5].

The final product (ingot, shielding block, centrifugated steel cylinder, etc.) is homogeneous, stable, and has the remaining activity content bound in the metal. Melting can produce a conditioned waste form suitable for direct disposal.

Metal melting provides several advantages such as [4]:

- Extensively proven technology.
- High volume reduction. If recycling is possible, the volume reduction factor from the disposal perspective of up to 100 is possible.
- The end product is typically homogenous and stable with remaining activity content bound in the metal.
- The end product can be reused and recycled within nuclear or conventional metal industry.

3 THE RELEVANCE OF METAL MELTING IN SLOVAKIA

Two nuclear power plants are being decommissioned in Jaslovské Bohunice, Slovakia. One is A1 NPP (heavy water gas cooled reactor) shut down in 1977 after an accident with local consequences (level 4 in the INES scale) after five years of operation. Decommissioning of this NPP has started in 1998 and should end late in 2033. Its decommissioning is very difficult due to the high contamination of the primary circuit. The second NPP in decommissioning process is V1 NPP (Russian type of pressurized water reactor, VVER-440 twin unit) shut down after 28 years of standard operation. Decommissioning of V1 NPP started in 2011 and should end in 2025. Both NPPs present a potential source of large amount of low level metallic radioactive waste suitable for decontamination and recycling. As mentioned earlier, metal melting is a suitable

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decontamination technology that could be helpful during the decommissioning of the aforementioned NPPs. At present no melting unit is commissioned in Slovakia but it is planned to construct and commission such a facility in the near future. Application of metal melting in the waste management strategy could lead to releasing considerable volume of scrap metal arisen from both Slovak NPPs that are currently being decommissioned and also from NPPs that will be decommissioned in the future. The melting technology can be also considered for volume reduction prior to disposal.

4 RADIATION IMPACT ON THE WORKERS DUING THE MELTING

Metal melting is a complex process starting by delivery of radioactive scrap metal to the melting facility, ending by releasing of metal ingots to the environment for restricted or unrestricted reuse. As mentioned above, the paper deals with the evaluation of exposure of the workers, specifically of the scrap truck driver, scrap cutter, furnace operator, slag remover, ingot caster and ingot handler.

4.1 General assumptions of model calculation

In the calculation of radiation impacts of selected workers the following considerations were taken into account:

- Melting facility comprises an induction furnace of charge size of approximatelly 2 tonnes of scrap metal.
- The melting facility is able to melt two batches per one workday, *ie*, approx. 4 tonnes of scrap metal.
- 250 workdays per year are considered, *ie*, the annual capacity of the melting facility is approximatelly 1 000 tonnes of scrap metal
- Radiological limitation for the facility is 1 000 Bq/g for total β/γ activity (it is conservatively considered that the workers melt the entire year scrap metal with maximum allowed activity).
- Considered exposure pathways are external as well as internal.
- For the calculation one nuclide vector is used. This nuclide vector characterizes the radiological situation of NPP shut down after fuel accident (A1 NPP). Its composition is shown in Tab. 1.
- During melting, radioactivity distribution coefficients for each radionuclide are considered. It is necessary to know the fraction of the activity originally present in radioactive scrap metal which may be transferred to the ingot, to the slag and to the dust after melting. These coefficients were adopted from the experience obtained in the CARLA Plant, Germany [6] and from publication NUREG-1640" [7] and are shown in Tab. 1.
- Mass partitioning factors for the melt, slag and dust are considered (98.35% for melt/ingot, 1.64% for slag and 0.01% for filter dust) [8].

Table 1. Nuclide vector composition and radioactivity distribution coefficients during melting used in calculations, [6,7]

Radio -nuclide	Share (%)	Half-life (yr)	Distribution (%) Melt	Slag	Dust
^{137}Cs	48.41	30.0	1	60	39
^{90}Sr	32.66	28.7	1	97	2
^{63}Ni	13.15	100	90	10	0
^{60}Co	2.77	5.27	88	11	1
^{241}Am	1.28	432	1	97	2
^{152}Eu	0.75	13.5	4	95	1
^{239}Pu	0.60	24100	1	97	2
^{151}Sm	0.37	90	0	93	7

4.2 General description of worker scenarios

For dose assessment purposes, six representative worker scenarios for metal melting were developed. In the following paragraphs a brief description of selected workers is given.

The *truck driver* scenario models the potential dose to a worker who transports contaminated scrap metal from the place of its origin to the melting facility. It is estimated that one worker would spend approx. one and half hour driving the truck to the melting facility. Considering that scrap metal is transported in ISO container with maximum load of 28 tonnes, the worker would perform 36 transports to transport 1 000 tonnes of contaminated scrap metal annually. Since the melting facility and decommissioned NPPs are in the same locality, the truck driver scenario is relevant only for metallic radioactive waste arisen outside locality Jaslovské Bohunice.

The *scrap cutter* scenario models a worker who prepares the scrap for delivery to the furnace. This workers activity includes shredding, cutting and sorting of scrap metal. It is estimated that the worker would have to work 6 hours per day to process approx. 4 tonnes of scrap metal.

The *furnace operator* scenario models the potential dose to a worker who operates the furnace in the furnace control room. It is considered that this worker, besides operating the furnace during the melting, also operates the crane and loads scrap metal into the furnace. It is estimated that the worker has to work approx. 3 hours per day to load and melt two batches, *ie*, 4 tonnes of scrap metal.

The *slag remover* scenario models the potential dose to a worker who uses standard loading and unloading equipment to handle the slag by-product at the melting facility. In general, slag can be removed in several different ways, *ie*, removed from the top of the furnace manually or by a manipulator (crane), casted into ingot MOVLD and removed after cooling. In the calculations it is assumed that the worker removes the slag manually from the melt bath surface. It is estimated that the worker would have to work 1.5 hours per day to process the slag from two batches.

The *ingot caster* scenario models a worker casting metal ingots. The melt is casted into 400 kg ingot moulds. It is estimated that the worker would have to work 2 hours per day to cast 10 ingots.

The *ingot handler* scenario models the potential dose to a worker manipulating with the ingots. This workers activity includes pulling out the ingots of the ingot moulds and its replacement to 200 L drums. The ingots are measured in a gamma scanner for residual activity and subsequently free released or transported to the interim storage facility. It is estimated that the worker manipulates the ingots approx. 2 hour daily.

4.3 Radiological impact assessment method

The main purpose of the paper is to assess radiation impacts of the workers during the melting of contaminated scrap metal. Generic radiation exposure scenarios were used to conceptually model situations regarding melting. These scenarios are a combination of radiation exposure pathways containing specific exposure conditions. Three main exposure pathways are considered in calculations: exposure to external radiation, inhalation of radioactive small particles or gases and ingestion of radioactive materials. In the following chapters formulas for the assessment of particular exposure pathways are described [9,10]. Calculation of external exposure was performed using the computational tool VISIPLAN 3D ALARA Planning Tool.

External exposure (VISIPLAN 3D ALARA description)

VISIPLAN, developed in Belgium, is an appropriate tool for evaluation of external gamma and X-ray exposure. This tool allows modelling of real scenarios, hence the obtained results can be beneficial for nuclear management practices. Using this tool, decommissioners can model from simple up to complex geometries, thus providing reliable results. VISIPLAN can be also used for radiation protection purposes in nuclear installations decommissioning and waste management strategy [11-13].

The method used in VISIPLAN is based on a point-kernel calculation with a build-up correction, where the volume source is divided into point sources. The photon fluency rate at a dose point is then determined by superposition of partial dose contributions from single point sources

$$\Phi = \int_V \frac{SBe^{-b}q}{4\pi r^2}\mathrm{d}V \qquad (1)$$

where: S is the source strength per unit volume (n/s), B is the build-up factor (-), b is an dimensionless term which represents the attenuation effectiveness of the shield, r is the distance from a point source (m), and V is the volume m^3).

Point sources are called kernels and the process of integration, where the contributions to the dose from each point is added up, is called a point-kernel method [14].

Inhalation

For the inhalation exposure, the following formula was used [9]

$$E_{\mathrm{inh},C} = E_{\mathrm{inh}} t_e f_d f_c C\mathrm{dust} V e^{-\lambda t_1} \frac{1-e^{-\lambda t_2}}{\lambda t_2} \qquad (2)$$

where: $E_{\mathrm{inh},C}$ – is the committed effective dose in a year from inhalation per unit activity concentration in the material ((μSv/a)/(Bq/g)), E_{inh} – is the effective dose coefficient for inhalation (μSv/Bq), t_e – is the exposure time (h/a), f_d – is the dilution factor (-), f_c – is the concentration factor of specific activity in the fine fraction (-), Cdust – is the effective dust concentration in the air (g/m^3), V – is the breathing rate (m^3/h), λ – is the radioactive decay constant (1/a), t_1 – is the decay time before the start of the scenario (a), and t_2 – is the decay time during the scenario (a).

Ingestion

For the ingestion exposure, the following formula was used [9]

$$E_{\mathrm{ing},C} = E_{\mathrm{ing}} q f_d f_c f_t e^{-\lambda t_1} \frac{1-e^{-\lambda t_2}}{\lambda t_2} \qquad (3)$$

where: $E_{\mathrm{ing},C}$ – is the committed dose in a year from ingestion per unit activity concentration in the material ((μSv/a)/(Bq/g)), e_{ing} – is the effective dose coefficient for ingestion (μSv/Bq), q – is the ingested quantity per year (g/a), f_d – is the dilution factor (-), f_c – is the concentration factor in the fine fraction (-), f_t – is the root transfer factor (-), λ – is the radioactive decay constant (1/a), t_1 – is the decay time before the start of the scenario (a), and t_2 – is the decay time during the scenario (a).

5 RESULTS

The results presented in this paper are based on generic exposure scenarios and pathways analyses using one nuclide vector composition, which represents the radiological situation of NPP shut down after fuel accident.

The obtained results for the described worker scenarios are shown in Tab. 2. As one can see, the absorbed dose depends on several factors such as the dominant radionuclides in the nuclide vector, radioactivity distribution during the melting, time of performed activity, *etc.*

According to the obtained results, the slag remover receives the highest effective dose because he works with the secondary radioactive waste with relatively high concentrations of several radionuclides. As it was mentioned in the chapter describing the melting technology, decontamination effect is much higher for fission products as

Table 2. Results obtained for melting of the scrap metal

Absorbed effective dose (mSv/a)				
	Inhalation	Ingestion	External exposure	Sum
Truck driver	–	–	1.66×10^{-1}	1.66×10^{-1}
Scrap cutter	7.90×10^{-2}	1.45×10^{-2}	7.50	7.59
Furnace operator	–	–	1.28	1.28
Slag remover	1.87	1.56×10^{-1}	6.50	8.53
Ingot caster	5.37×10^{-4}	7.12×10^{-5}	2.00×10^{-1}	2.01×10^{-1}
Ingot handler	4.03×10^{-4}	2.37×10^{-5}	8.50×10^{-2}	8.54×10^{-2}

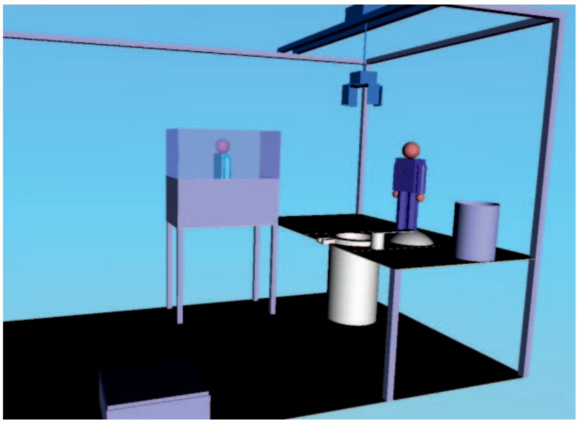

Fig. 1. Furnace operator and slag remover modelled in VISIPLAN 3D ALARA

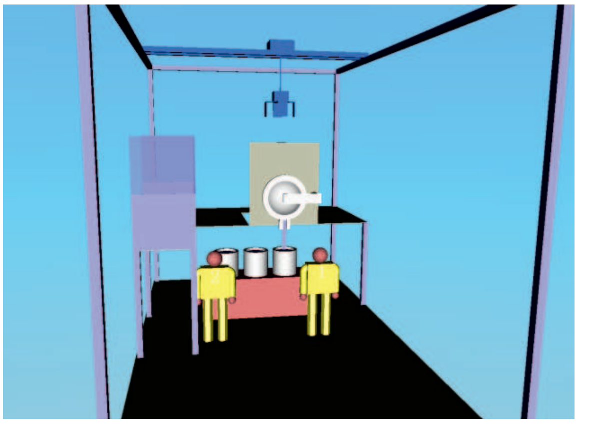

Fig. 2. Workers during casting the ingots modelled in VISIPLAN 3D ALARA

well as for transuranium elements which are mostly redistributed to the slag. The lowest dose is received by the worker during ingot manipulations because the ingot is decontaminated and the residual activity is caused only by low concentrations of activation products.

Generally it can be said that external exposure in comparison with internal exposure is dominant, the only exception is removing the slag because the slag remover works with secondary RAW with high concentrations of fission products as well as actinides.

VISIPLAN 3D ALARA code also allows graphical representations of the obtained results. Some of these figures can be seen below (Figs. 1 and 2).

6 SECONDARY RADIOACTIVE WASTE

During the melting of contaminated scrap metal, secondary radioactive waste is generated like fragmentation residues, slag, dust, spent filters, furnace lining, *etc.*

Normally, the amount of the slag is in the range of 1 to 4% (by weight) depending on the furnace properties as well as melting conditions (e.g., slag former). As it was stated in chapter 4.1 the considered amount of the slag in the calculations is 1.64%. The amount of produced dust was stated to be 0.01%. The furnace lining suffers from degradation and after several melting cycles it has to be replaced by a new one. The lifetime of the furnace lining depends on its type. Lining made of material with acidic nature has a lifetime of approx. 55 melting cycles and weight 1.2 tons. Lining made of neutral nature mullitic material has a lifetime of approx. 110 melting cycles and weight 1.8 tones.

According to the assumptions mentioned above, the annual production of selected secondary radioactive waste was estimated as follows:

- Slag: 16.4 tonnes,
- Dust: 0.1 tonnes,
- Furnace lining: 8.2 to 10.9 tonnes (depends on furnace lining type used during the year).

The secondary waste should be packed into 200 L drums and delivered to the treatment facility, where all waste is treated, conditioned and packed in an appropriate waste package. Waste packages are subsequently disposed in the disposal facility in Mochovce.

7 DISCUSSION AND CONCLUSIONS

The main goal of the paper is to evaluate the radiation impact upon the workers during the melting of contaminated scrap metal. The received effective dose depends on the performing activity as well as on the radionuclide present in the scrap metal as contaminant and radioactivity distribution coefficients during melting. The highest effective dose is absorbed by the slag worker (8.53 mSv annually) because of manual manipulation with the slag.

In general it can be said that external exposure pathways are much more relevant than internal exposure pathway. The workers in the melting facility wear protective suits during melting and preparation works result in minimal ingested or inhaled dust.

It is important to note that the evaluated worker scenarios are basic tasks during melting. Complex assessment of the metal melting process requires evaluation of all activities related to melting, e.g., change of used furnace lining, manipulation with collected dust from the ventilation system, transport of ingots to the ingot storage yard, *etc*.

The mentioned values (absorbed effective doses) meet legislatively given limits in the Slovak Republic, in which a value of 20 mSv [15] is defined as the maximum allowed dose received by a worker annually.

The total weight of generated secondary waste is up to 27.4 tonnes considering only slag, collected dust and furnace lining. It is also important to estimate the amount of other secondary RAW like fragmentation residues, spent filters, equipment and spent ingot moulds. As one can see from the results, the considered secondary waste is only 2.74

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