RADIATION EXPOSURE TO THE GENERAL PUBLIC FROM RECLAIMED METALS OUT OF NUCLEAR FACILITIES

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ABSTRACT

A significant amount of metal scrap results from decommissioning and refurbishing nuclear installations. A large percent of this scrap can be safely exempted from control and recycled. In Germany the release of metal from a control zone requires proof that radiological harm to the population does not occur. In order to analyze the radiological impact of exempting metal a stochastic model was developed, which realistically includes improbable scenarios and most likely scenarios as well as integrating information about the dose level and the number of exposures in a single analysis. Impact analyses were conducted for ferrous metal, aluminum and copper based metals which were released, melted and formed into new products. The case of α-contamination was treated separately.

INTRODUCTION

During the course of operating and decommissioning a nuclear facility a significant amount of slightly contaminated or activated equipment and material results. From an ecological and environmental stand point the first priority should be to decontaminate and recycle this material. This is also the intention of the German Atomic Energy Act paragraph 9a which requires that material must be recycled if it is radiologically sound and economically acceptable (1). This lecture presents a systematic method for studying the radiological consequences of releasing slightly activated or contaminated metallic material from a control zone. The analysis method presented here has been used by the German government to make exemption level decisions (2,3). The German realization of exemption levels will not be presented here but are discussed in the lecture by Prof. Neider. Once the metal has been exempt from control it is assumed to be treated as normal scrap. The economic feasibility of exempting metal depends on the decontamination costs versus the cost of final storage, which is not discussed.

In the IAEA Safety Series no. 89 (4), a trivial level for the individual effective dose equivalent is argued to be between 10 - 100 μSv/yr. The value of 10 μSv/yr, which allows exposure to multiple sources while still remaining under 100 μSv/yr, has found international acceptance as a guide for the maximum dose for an average member of a critical group due to any single exposure pathway. The consensus as to a trivial dose, also known as "de Minims" concept, is the first important step to setting exemption levels. The problem, and topic of this presentation, is how to convert the 10 μSv/yr dose into a measurable quantity which can be applied to material leaving a control zone. The dose depends on a large number of quantities, many of which are not directly measurable, or vary over a wide range in a stochastic manner. Such quantities as the amount of material, the nuclide vector and the specific activity can be measured directly at the control area. Other important quantities like breathing rate, distance from an object and the number of hours spent near or working with a radioactive object are not determinable without strict accounting procedures. Accounting procedures are neither economically practical nor in accordance with the goal of finding exemption levels.

In a number of studies (5,6) scenarios describing the contact with contaminated or activated metal are presented and equations for calculating doses from the activity are developed. Such studies describe the typical way the metal is used and in which sectors of the society the reuse occurs, like smelting and reforming into frying pans. The parameters selected to make the calculations are based on available data and well educated guesses. One weakness of such evaluations is that the parameters are represented by single values, while in reality they vary over a wide range. A second weakness is that such evaluation methods do not consider the interconnected nature of the scenarios. For example if 100 tons of metal are melted down, radiation exposure from the smelting process will result as well as from using the new products. In order to develop a globally consistent approach the interconnected scenarios must be combined into one radiological impact study for the release of a given quantity of metal.

The variability of the parameters involved in evaluating the radiological impact of metal released from a control zone leads naturally to the use of stochastic tools and statistical evaluation. We present a systematic and globally consistent method for evaluating the impact by using a Monte Carlo simulation. The model is constructed by including many scenarios which describe the possible ways in which people and workers can be exposed to the radioactive metal. The parameters used to calculate the scenarios are allowed to vary within realistic bounds so that for each calculation of a scenario a different dose results. The scenarios are then coupled together to describe the various ways the metal can proceed from being released to a final product. The simulation is then

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realized by releasing a given amount of metal and allowing the computer to select which portion of the metal will be found in which combination of scenarios, depending on the predetermined probabilities of occurrence. The computer also selects values for the scenario parameters, depending on the allowed variation. Multiple scenarios for the same metal, such as transport and foundry, are possible and necessary but the metal cannot be used twice, that is if a frying pan is made the metal can not also be part of a car, mass conservation is respected. This type of analysis realistically models what actually occurs when metal is released from a nuclear installation and can be used to investigate such questions as, what happens when the decommissioning activities are increased by 10 fold? The results of a stochastic simulation are not single values, as is the case for deterministic evaluations, but instead are given in terms of a distribution of doses on which statistics can be performed. The selection of which scenarios are relevant, the range in which the scenario parameters are allowed to vary and the probability that a particular scenario will be chosen are critical to the outcome of the simulation. These data must be supplied to the model from measurements or *realistic* estimations. It is nevertheless more realistic and easier to assign a range of values for a parameter than to give it a single value as is done in deterministic calculations.

STOCHASTIC MODELS

The stochastic model of the release of ferrous metal which is not contaminated with α-emitting radionuclides is presented in some detail. Non-α-contaminated ferrous metal represents the majority of the material released from German nuclear power plants of the light water reactor (LWR) type (10). The results from three further stochastic models, one for aluminum, one for copper based metals and one for α-contaminated metal, are briefly discussed. In Table I a few representative nuclide vectors with their origins are presented. Each nuclide vector leads to a different dose conversion factor. The models account for the different nuclide vectors by allowing the conversion factors to vary. Dose conversion factors are taken from the ICRP tables (7).

TABLE I

Nuclide Vectors

Light Water Reactors (15, 16)			Uranium Fuel Production (17)	
Radionuclide	Path Finder [Bq]	GKN-1 [%]	Radionuclide	[%]
Mn-54	*	0.8	U -234	0.61
Fe-55	$3.0 \cdot 10^8$	*	U -235	0.023
Ni-59	$3.7 \cdot 10^6$	*	U -238	0.11
Co-60	$3.9 \cdot 10^9$	97.4	Pa-234m	0.11
Ni-63	$5.3 \cdot 10^8$	*	Pa-234	10^{-4}
Ag-108m	$1.3 \cdot 10^6$	*	Pa-231	10^{-6}
Sb-125	*	1	Th-230	10^{-4}
Cs-137	$4.4 \cdot 10^6$	0.8	Th-231	0.023
Eu-152	$7.0 \cdot 10^4$	*	Th-234	0.11
Pu-238	$3.0 \cdot 10^4$	*		
Pu-239, Pu-240	$8.5 \cdot 10^3$	*		
Am-241	$8.1 \cdot 10^3$	*		

* data not supplied

The first step towards developing an integrated model for the calculation of doses to the public is to determine the possible ways the released material can be used after being exempt from further control. For metal leaving a nuclear facility the flow chart in Fig. 1 gives an overview of the expected uses of the released material. A large percentage will be melted down and reformed into new products, while a lesser portion could be directly reused. For example tools used in refurbishing work or electric motors are good examples of objects which might be directly reused. This is the first major differentiation made in the radiological impact analysis. In principle once an object has been exempt it is impossible to guarantee that it will not be directly reused. The decision how to apply exemption levels must take this into account.

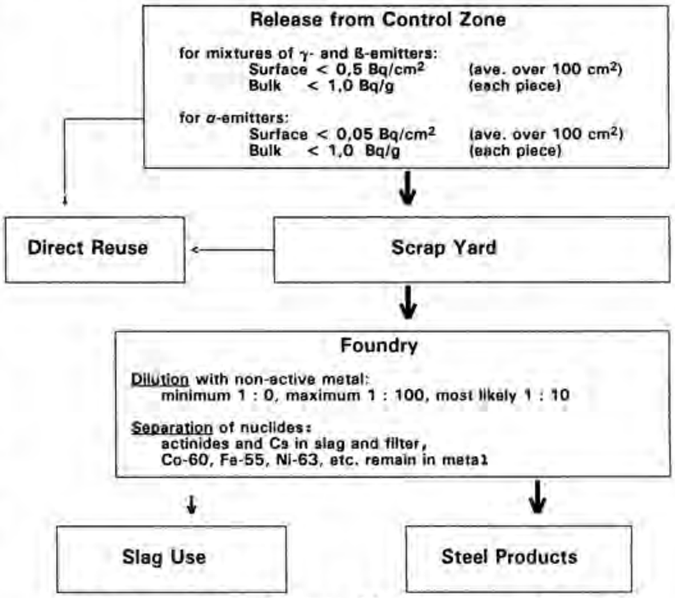

Fig. 1. Flow chart for metal leaving a control zone.

Melting the metal separates the radionuclides depending on their chemical characteristics (6, 8). More than 90% of the actinides and Cs end up in the slag and filters, while such nuclides as Co, Fe, Ni and Mg remain in the product steel. In Fig. 1 this is indicated by considering two pathways, one for the products and a second for the slag. The α- and ß-emitters and weak γ-emitters which remain in the metal product lose importance since they are homogeneously bound up in the metal which shields against exposure. The slag can be used for example as a cover for parking lots or sporting facilities. These uses lead to exposures due to inhalation, ingestion and irradiation.

Beside the chemical characteristics the radiological impact also depends on the total amount of activity released and the dilution of the exempt metal with ore and scrap not originating from nuclear facilities. At the end of 1986 the total amount of scrap originating from nuclear facilities which had been recycled amounted to about $9 \cdot 10^3$ tons (9). The average activity is difficult to determine and depends strongly on the origin of the metal, nevertheless reasonable estimations put it between 0.01 and 0.1 Bq/g (10). Comparing the $9 \cdot 10^3$ tons from the nuclear industry to $12 \cdot 10^6$ tons, which is the total scrap bought by the steel works in 1990 in the former FRG (before unification) (11), one can see that the metal coming from nuclear installations is only a minor part of the total scrap metal industry. This demonstrates that on a global scale the radioactive scrap is significantly diluted, although in an extreme example a small scrap yard could receive the entirety of the released material from a decommissioning project, so that at some point a significant percentage of its inventory could be slightly radioactive. If this scrap yard delivered a complete oven charge of its radioactive material to the foundry, then the product metal would have the same average activity as the scrap. Generally one assumes that a dilution of the slightly radioactive scrap with non-radioactive scrap occurs in the smelting process (6,10).

The models consider 57 different ovens used in the German steel industry, such as oxygen blast furnace, electric arc, etc. (10). Depending on which oven is used the amount of scrap added to the charge can range from 0% to 100%. The size of the charge also depends on the oven. The model allows for no dilution to a dilution of 1 part radioactive to 100 parts non-radioactive with the most likely value being a 1:10 dilution. The computer selects an oven, dilution ratio and a quantity of metal released from a control zone which is contaminated or activated or both and calculates the mass and activity of the resulting charge. For each piece coming out of the control zone the computer assigns it an activity level (on the average 10% are assumed to be activated) and a surface contamination level, depending on whether the piece has been decontaminated or released without decontamination. The maximum activity and contamination allowed depend on the exemption levels.

The following description considers the radiological impact of the production of new products from melted down parts of a nuclear facility. The equations used to calculate the doses will not be presented here but are readily available in many publications (5,6). It is not the equations which are important here but instead the global approach to the problem. The presentation will therefore only point out the exposure situations which were considered (see Fig. 2).

Table I shows that Co-60 is the main contributor to the nuclide vector for scrap from LWR's. Co-60 also emits the highest energy gammas and so determines the dose conversion factor for the nuclide vectors. Doses are received at every step in which people come in contact with the metal. Firstly the transport of the material to the scrap yard exposes the workers to external irradiation and inhalation from contaminated dust and corrosion shaken lose from the objects. At the scrap yard the material is separated and cut to size which requires the handling of the material. Once the metal is bought by a foundry it is transported again and melted down. The smelting process also leads to the release of aerosols which are inhaled by the workers or exhausted out of the foundry leading to exposure of the neighboring communities. External irradiation occurs as well. Finally the metal is reformed into products which are sold to the general public. The production as well as the use leads to external irradiation. Ingestion plays a minor role since the radioactive nuclides are bound up in the product metal, nevertheless the normal wear of a frying pan could lead to ingestion of radionuclides (5). In the model product use is divided up into different areas, private use (household), public use and work place. The area in which the metal is used determines such parameters as the maximum and minimum exposure times, maximum and minimum distance from the product, size of the product and how many people are exposed (see Fig. 2).

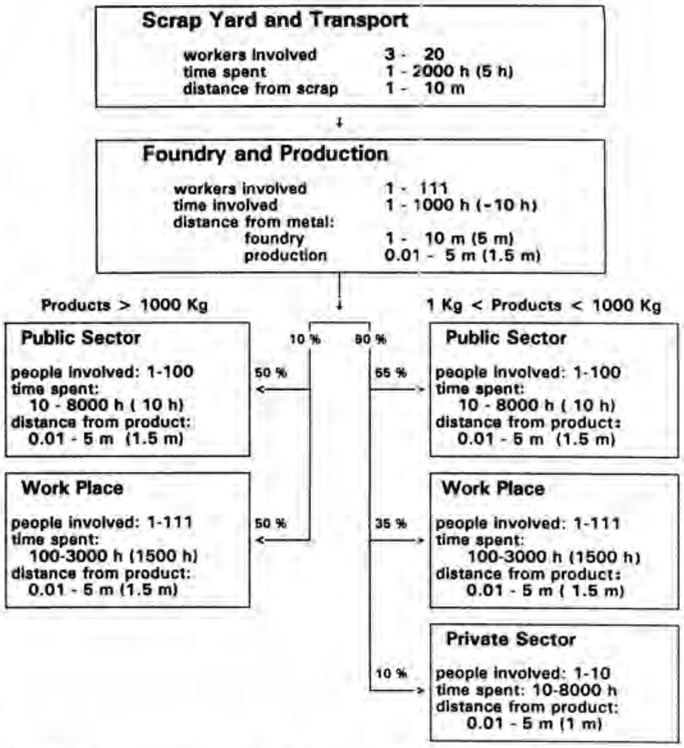

Fig. 2. Exposure scenarios for release of non-α-contaminated ferrous metal to be melted down into new products. Most likely values in parentheses.

The modelling technique as outlined is shown in the form of a flow chart in Fig. 2. Görtz et al. (10) demonstrated that external irradiation is the dose determining exposure for typical nuclide vectors from LWR's. In order to calculate doses the statistical input data for all the parameters need to be supplied. Since detailed statistical data are not always available we need to introduce a mathematical tool which helps to describe the data and makes calculation easier. A truncated Lorentz function is used to describe the statistics. Wherever possible, the Lorentz function is fitted to the data. Some of the input data have already been presented (Table I). If data needed for the construction of a distribution are not available, an educated guess is made which errs to the conservative side. That is the doses are more likely to be too large than too small. It is not possible to give all the input data here therefore we refer the interested reader to (10,12). Of course for a country other than Germany the input data will be different. Nevertheless the model demonstrates a technique to make realistic evaluations of the radiological impact of releasing metal from a nuclear facility.

A simulation starts with the release of metal. In the case of ferrous metal the starting quantity was chosen to be 1000 tons which reflects the expected annual quantity from decommissioning work (9). This metal is then transported in loads ranging from 0.5 to 40 tons to a scrap yard where it is unloaded, sorted and cut to size. The activity of the scrap is determined as discussed above. For each transport the doses received by the workers and drivers are calculated and tabulated. The doses received depend on the transport distance, the geometry, the sorting and processing procedures for the scrap, as well as on the activity and amount. The variations in the parameters are accounted for by allowing the exposure time, the number of workers and the distance from the scrap (calculated as a pile of scrap) to vary (values in Fig. 2). For each worker a dose is calculated by allowing the scenario parameters to vary within the allowed range, so that each worker receives a different dose.

From the scrap yard the metal goes to the foundry where it is melted down with other scrap and ore. The activity of the smelt product is determined as discussed above and the exposure of the foundry workers calculated. Once again the variables involved in the scenarios are allowed to vary. The model accounts for a number of further details like exposure of the same worker to multiple radioactive changes, production of a large object like a ship and large and small companies (10).

Product use leads to the largest doses for metal contaminated with Co-60 dominated nuclide vectors. This is due to long exposure times and close contact with the products. Each charge of metal coming from the foundry is divided up into portions having different masses and geometries, which accounts for the many different products produced from steel. The exposure time, distance from the product and product size depend on where the product is used. Therefore the model distinguishes between; public use, private use and on the job use. Very large products are only found in the work place or in the public sector. For example a large drill press or lathe in the machining industry and a street car or airplane in the public sector. It is assumed that 10% of the steel forms very large objects (> 1 ton) and of these objects 50% are found in the public sector and 50% in the work place. The rest (90%) of the steel goes into making products with a mass between 1 and 1000 kg, which is divided up as follows; 10% private sector, 35% work place and 55% public sector (see Fig. 2). For each product the computer selects the number of people who are exposed, how long each person is exposed and at what distance (see Fig. 2). For example in the private sector the number of people exposed ranges between 1 and 10 (10 represents a large family), the exposure time for each person ranges between 10 h and 8000 h, most likely 1000 h, and the distance from the product between 0.01 and 5 m, most likely 1 m. The doses are calculated using these data and stored.

RESULTS

200 simulations were run and a statistical analysis performed on the results. The histogram in Fig. 3 shows the distribution of the doses for the ferrous metal without α-contamination. The abscissa is divided into dose ranges and the ordinate gives the average number of people per simulation who received a dose in that range. From the histogram one can see that the 10 μSv/yr limit is not strictly observed but that in a few cases higher doses occur. In Table II the percentile values for the models studied here are listed. The H_{50} value is interpreted to mean that in 50% of the simulations the highest dose calculated was less than this value. The two values H_{90} and H_{99} are to be interpreted similarly.

TABLE II

Procentile values [μSv/yr]

Model[a]	H_{50}	H_{90}	H_{99}	N_0[c]	N_1[d]
Ferrous Metal	13	33	69	210	10
Aluminium	8	19	50	116	9
Copper	6	11	20	40	1
α-Contaminated[b] Ferrous Metal	13	59	184	6	3

a) α-activity present only in the last model. Direct reuse is not taken into account.
b) Data from critical sector, manual treatment of scrap.
c) Average number of people receiving a dose between 3.16 and 10 μSv/yr.
d) Average number of people receiving a dose > 10 μSv/yr.

During decommissioning and refurbishing work on LWR's a large amount of aluminum, copper and copper alloys result which could be recycled. In Germany a recycling potential of about 30 tons of aluminum per year results from the nuclear industry (9,13). The amount of the copper and copper alloys coming from decommissioned nuclear installations (9,12,14) can be used to estimate the yearly amount of copper released in Germany. In the model 200 tons/yr is used for copper and 100 tons/yr for aluminum (12). Adjustments are needed in the above described model to reflect the details of recycling aluminum or copper. Some of the major points are the reduced expectation in quantity as compared to ferrous metals, the density differences and the different oven types. The model structure is the same and the nuclide vectors are expected to be similar to the ferrous metal (12). The resulting dose distributions from simulating the release of 100 tons of

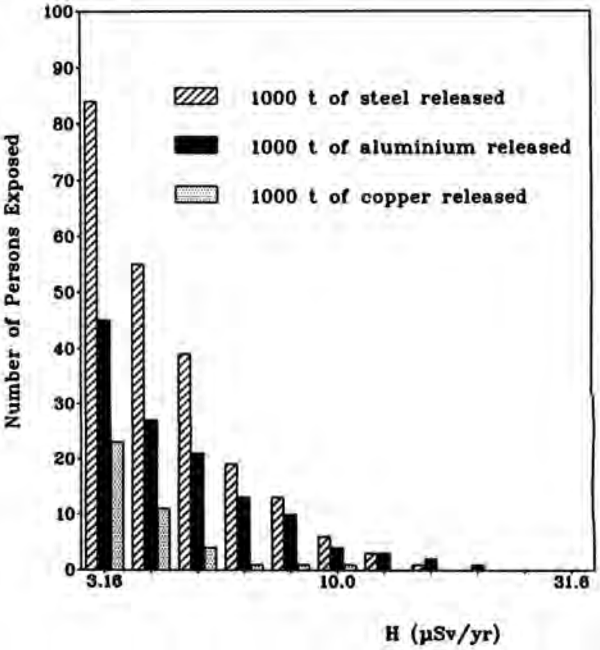

Fig. 3. Average individual dose histogram from 200 simulations.

aluminum and 200 tons of copper are plotted in Fig. 3. The H_{50}, H_{90} and H_{99} values are given in Table II. Comparing the results to those from the ferrous metals it can be seen that the radiological impact is approximately equal. If the amount of decommissioning activity is increased it is expected that the proportion of each metal to the total will remain about equal. This may not be the case when enrichment plants are decommissioned since they contain a significantly higher percentage of aluminum, although it will be predominantly α-contaminated which is not considered by this model.

Nuclear installations involved in the production of nuclear fuel are contaminated with α-emitting nuclides. Metal coming from these plants must be analyzed differently since the largest doses no longer come from external irradiation but most probably from inhalation. Secondly the α-emitters are, for the most part, separated out of the product metal into the slag (6,8) so that the product use becomes radiologically less important. The most significant sector is the processing of the scrap since this leads to the release of the radionuclides in the form of dust and aerosols (15). Using the same guiding principles as described above, a model for the recycling of α-contaminated scrap was developed. The set of critical scenarios are different from those described above. For α-emitting nuclides, cutting the metal by hand is the most critical scenario. The next most significant scenarios, breathing dust during smelting and using a slag covered sporting field or parking lot, give doses a factor 10 smaller. In Table II the percentile values for the manual cutting of α-contaminated scrap are shown.

CONCLUSIONS

The radiological impact analysis done here is for the case of melting down the exempted metal and reforming it into new products. If the metal objects are directly reused then a number of major differences must be considered. Probably the most significant difference is that no dilution of the activity occurs due to mixing with non-radioactive scrap in the smelting process. Before being melted the activity is normally neither fixed nor homogeneously distributed throughout the exempted object. These factors can lead to large doses depending on the scenarios considered. For example if a private person strips the paint from a metal cabinet and sands the surface in his basement where the ventilation is poor he could receive a dose as large as several 100 μSv if the surface is contaminated with α-emitters (12). Such scenarios must be considered and could in principle be built into the stochastic models described. The quantity of scrap which could be directly reused is small compared to the total exempted metal, therefore these scenarios have not been considered in this study.

The strength of using a Monte Carlo model to simulate the exemption of metal from a control zone lies in the ability to realistically represent the variation in the parameters and scenarios. Instead of making decisions based on one improbable critical scenario, the decisions can be made by considering the global impact. The improbable critical scenarios are not excluded by the model but instead put into relation with the normal case. For example, in the case of non-α-contaminated ferrous metal, out of the 200 simulations only one person got a dose greater than 100 μSv/yr, generally the worst case in a single simulation was less than 30 μSv/yr. The analysis method presented here also allows one to estimate the extent of the exposure. In the case of α-contaminated scrap the number of people exposed is relatively small, 9 (Table II), since the radionuclides are removed from the metal in the melting process. For nuclide vectors like that presented in the first column of Table I the critical sector is product use which exposes large numbers of people, 220. The advantage of the impact analysis method presented here is two fold; firstly its ability to realistically include the improbable cases and most likely scenarios in a single integrated analysis and secondly the integration of information about the dose level and the number of exposures in a single analysis.

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