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Assessment of Potential Risk due to Accidental Melting of Scrap Metal Containing Depleted Uranium Using a Computational Method

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Abstract: Depleted uranium (DU) has a beneficial use, such as ballast in aircraft and radiation shielding. Due to the chemical and radiological toxicity it may have adverse consequences to human health, particularly if it enters the body through inhalation, ingestion or wounding. One significant problem area, when working with DU, comes from finely divided airborne particles, which can result from some manufacturing operations such as machining and grinding. In this study RESRAD-Recycle computer code is used to estimate the exposure of workers and public to the recycling of scrap metal including depleted uranium and to evaluate the risk. Two general types of exposure scenarios have been incorporated into RESRAD-Recycle. The First scenario (worker scenario), evaluates worker's doses during the recycled material process. The second scenario (product scenario), determines public dose and risk from the use or exposure to products made of contaminated scrap metal. The obtained results indicate that the slag worker exposed to the highest dose and risk. In addition, the produced products cause a public hazard. Therefore, strengthen the nuclear safety and security regulations to this material type is mandatory. Spreading safety, security and safeguard culture is requisite to reduce the hazards of the radioactive materials.

Keywords: Depleted Uranium, RESRAD-Recycle Computer Code, Dose, Recycled Radioactive Materials

1. Introduction

Depleted uranium differs from natural uranium by having most of its U-235 and U-234 isotopes removed in the enrichment proses for nuclear fuel or weapons. However, its chemical and biological behavior is virtually identical to that of natural uranium [1]. Depleted uranium (DU) has a beneficial use, such as ballast in aircraft and radiation shielding. Due to the chemical and radiological toxicity it may have adverse consequences to human health, particularly if it enters the body through inhalation, ingestion or wounding. One significant problem area, when working with DU, comes from finely divided airborne particles, which can result from some manufacturing operations such as machining and grinding. Recently, depleted uranium (DU) use in peaceful applications are increased widely, since it is nearly twice as dense as lead. It can be used as counterweights or ballast in aircraft, parts of shielding material in a radiotherapy machine as well as container for the transport of radioactive materials [2]. Depleted counterweights used in the aircraft are triangular prisms manufactured from cast depleted uranium (DU). The counterweights are flash coated and painted with a primer to reduce surface oxidation [3]. In a typical sample of depleted uranium, most of the weight (99.8%) consists of atoms of U-238. about (0.2%) of the weight consists of atoms of U-235, and a very small amount (0.0006% by weight) is U-234. Thus, ^{238}U isotope in DU is the radiological concern. Radioactivity emitted from uranium isotopes consists of alpha particles and gamma rays. Activity of DU is 14.80 Bq/mg which is about 58% of the activity of natural uranium. DU is 3 million times less radioactive than ^{226}Ra (still found in many old luminous clocks and watches) and 10 million times less radioactive than ^{241}Am, which is found in commercial fire detectors [4-5]. The radiological hazards of any radioactive material are proportional to the amount of radioactivity present. The various uranium isotopes, and mixtures of those isotopes, can be characterized by their "specific activity", defined as the amount of radioactivity (in Curies) per unit of mass (in gram). Radionuclides with longer half-lives have smaller specific activities [6]. Because of U-238 has very long half-life, the effects of decay on its concentration is not significant for short time periods [7]. The ^{238}u is an alpha emitter and as such poses no real risk to any of the sensitive tissues of the body including the lenses of the eyes a t a depth of 3 mm and the basal layer of the epidermis at 70 pm. This nonpenetrating radiation interacts only with the outer dermal layer and, at scenario atmospheric levels, would have no significant effect. The beta radiation in the plume could pose a hazard to uncovered skin, and gamma radiation would contribute to the whole-body dose. However, these dose contributions are expected to be insignificant [8].

Therefore, exposure effect of DU is mainly the result of its ingestion, inhalation and dermal contact [9]. Entry of uranium into the body thus results in a combined chemical/radiation exposure. In the work place or the environment, the radiological hazards from DU are primarily due to alpha particle emission. This means that the internal radiation dose from ingestion or inhalation of uranium compounds is the limiting hazard under almost all circumstances [10]. Beta and gamma components are only the DU contribute to external dose where the affected organ is the skin, External exposure to DU occurs when fragments are picked up [11, 12]. Potentially depleted uranium has both chemical and radiological toxicity with the two important target organs being the kidneys and the lungs. Health consequences are determined by the physical and chemical nature of the depleted uranium to which an individual is exposed, and to the level and duration of exposure. Ingestion of DU is not considered the major exposure pathway [13]. Inhalation of dust is considered the major pathway for DU exposure. It is essential to provide machine ventilation, area ventilation and special filtering equipment to protect workers from radioactive dust and particles that could be inhaled or ingested [14]. Like any radioactive material, there is a risk of developing cancer from exposure to radiation emitted by natural and depleted uranium. The annual dose limit set by the IAEA for a member of the public is 1 mSv, while the corresponding limit for a radiation worker is 20 mSv. The additional risk of fatal cancer associated with a dose of 1 mSv is assumed to be about 1 in 20,000. This small increase in lifetime risk should be considered in light of the risk of 1 in 5 that everyone has of developing a fatal cancer. It must also be noted that cancer may not become apparent until many years after exposure to a radioactive material [15].

2. Material and Method

The RESRAD-RECYCLE computer code is a pathway analysis tool designed to calculate potential radiation doses and risks resulting from recycling of radioactive scrap metal and the reuse of surface-contaminated material and equipment RESRAD-RECYLE is a member of the RESRAD family of codes developed by Argonne National Laboratory USA department of energy.

I Description of the scenarios

Two general types of exposure scenarios have been incorporated into RESRAD-RECYCLE:

1 Worker scenarios:

For evaluating the dose and risk to workers who process recycled materials

The worker scenarios model potential exposures are associated with:

a) The transport of radioactive scrap metal from the place of origin to the smelter (step 1, scrap delivery),
b) The smelting process and manufacture of metal ingots for industrial products (step 2, scrap smelting),
c) Transport of metal ingots to product fabrication plants (step3 ingot delivery),
d) Product fabrication (step 4, initial and final fabrications)

2 End-use product scenarios:

For evaluating the dose and risk to persons using or otherwise being exposed to products made of recycled radioactive materials [16].

The Consumer scenarios are including:

a) public products (pavement, bridges and buildings),
b) surface contaminated reuse products (tools and contaminated buildings)

II Model input parameters:

A postulated accident Depleted uranium with weight of 150 Kg was missing and that managed to pass through the scrap metal recycling plant. The input model parameters are illustrated in Table 1.

Table 1. *Input Parameters of Selected Scenarios.*

Scenario		Dilution Fraction	Exp Time hr	Dust Load g/m^3	Resp Fract	Inh Rate m^3/hr	Inh Protec Factor	Ing Rate g/hr
Scrap Delivery:	Scrap Cutter	1.00E+00	1.20E+01	5.00E-04	1.00E-01	1.20E+00	1.00E+00	6.25E-03
Scrap Delivery:	Scrap Loader	1.00E+00	4.00E+00	5.00E-04	1.00E-01	1.20E+00	1.00E+00	6.25E-03
Scrap Delivery:	Scrap Truck Driver	1.00E+00	4.00E+00	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Scrap Smelting:	Scrap Processor	1.00E+00	1.20E+01	1.00E-04	1.00E-01	1.20E+00	1.00E+00	6.25E-03
Scrap Smelting:	Smelter Yard Worker	1.00E+00	8.00E+01	1.00E-04	1.00E-01	1.20E+00	1.00E+00	6.25E-03
Scrap Smelting:	Smelter Loader	1.00E+00	4.00E+00	1.00E-03	1.00E-01	1.20E+00	1.00E+00	6.25E-03
Scrap Smelting:	Furnance Operator	1.00E+00	5.00E+00	1.00E-03	1.00E-01	1.20E+00	1.00E+00	6.25E-03
Scrap Smelting:	Baghouse Processor	1.00E+00	1.00E+00	1.00E-03	1.00E-01	1.20E+00	1.00E+00	6.25E-03

Scenario		Dilution Fraction	Exp Time hr	Dust Load g/m^3	Resp Fract	Inh Rate m^3/hr	Inh Protec Factor	Ing Rate g/hr
Scrap Smelting:	Refinery Worker	1.00E+00	5.00E+00	1.00E-03	1.00E-01	1.20E+00	1.00E+00	6.25E-03
Scrap Smelting:	Ingot Caster	1.00E+00	2.50E+00	1.00E-03	1.00E-01	1.20E+00	1.00E+00	6.25E-03
Scrap Smelting:	Small Objects Caster	1.00E+00	5.00E+01	1.00E-03	1.00E-01	1.20E+00	1.00E+00	6.25E-03
Scrap Smelting:	Slag Worker	1.00E+00	2.50E+01	1.00E-03	1.00E-01	1.20E+00	1.00E+00	6.25E-03
Ingot Delivery:	Ingot Loader	1.00E+00	2.00E+00	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Ingot Delivery:	Ingot Truck Driver	1.00E+00	5.00E+00	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Initial Fabrication:	Storage Yard Worker	1.00E+00	4.00E+01	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Initial Fabrication:	Sheet Maker	1.00E+00	1.00E+00	1.00E-04	1.00E-01	1.20E+00	1.00E+00	6.25E-03
Initial Fabrication:	Coil Maker	1.00E+00	1.00E+00	1.00E-04	1.00E-01	1.20E+00	1.00E+00	6.25E-03
Final Fabrication:	Sheet Handler	1.00E+00	1.00E+00	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Final Fabrication:	Coil Handler	1.00E+00	8.00E+01	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Product Distribution:	Product Loader	1.00E+00	2.00E+01	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Product Distribution:	Product Truck Driver	1.00E+00	8.00E+00	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Product Distribution:	Sheet Assembler	1.00E+00	2.00E+01	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Product Distribution:	Warehouse Worker	1.00E+00	2.00E+03	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Consumer Product:	Parking Lot	1.00E-02	6.20E+01	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Consumer Product:	Room/Office	1.00E+00	2.00E+03	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Consumer Product:	Appliance	1.00E+00	7.30E+02	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Consumer Product:	Automobile	1.00E+00	7.30E+02	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Consumer Product:	Office Furniture	1.00E+00	2.00E+03	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Consumer Product:	Home Furniture	1.00E+00	3.65E+03	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Consumer Product:	Frying Pan	1.00E+00	1.80E+02	0.00E+00	1.00E-01	0.00E+00	1.00E+00	4.12E-03
Public Product:	Pavement	1.00E-02	6.00E+00	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Public Product:	Building with Rebars	1.00E+00	2.00E+03	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Public Product:	Bridge	1.00E+00	1.00E+00	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Controlled Products:	Shield Block	1.00E+00	1.00E+00	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Controlled Products:	Radwaste Container	1.00E+00	1.00E+00	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00
Reuse Product:	Tool Reuse	1.00E-02	2.00E+03	1.00E-06	1.00E-01	1.20E+00	1.00E+00	1.00E-04
Reuse Product:	Building Reuse	1.00E-02	2.00E+03	1.00E-06	1.00E-01	1.20E+00	1.00E+00	1.00E-04
Scrap Transportation:	Public Exposure	1.00E+00	1.00E+00	0.00E+00	1.00E-01	0.00E+00	1.00E+00	0.00E+00

Note: For surface reuse scenarios, the dust load is the emission rate in (1/hr), the ingestion rate is in (m^2/hr) and the dilution represents a surface transfer factor applied to inhalation and ingestion doses only.

Theoretical calculation for effective dose:

The estimated values of the external effective doses by the RESRAD – Recycle Code in this study results validated with the calculated values using the equation (1).

$$D=\frac{F_7 A}{X^2} \quad (1)$$

$$Eext = \frac{ACF_6 Te}{X^2} \quad (2)$$

Where:

D: Dose rat (mSvlh)

E_{ext} = Effective dose from a point source [mSv]

A = Source activity [kBq]

T_e = Exposure duration [h]

CF_6 = Conversion factor $2.3x10^{-1}$ [(mSv/h)/(kBq)] (For natural and depleted uranium it is assumed all of the release is U-238) [17]

F7: Conversion factor

X = Distance from the point source [m]

3. Result and Discussion

The output data effective doses for working and scrap delivery scenarios (including scrap cutter, scrap loader, scrap truck driver) for the total three uranium isotopes in DU of scrap metal are presented in Table 2. Also, smelting work scenarios include scrap processor, refinery worker, and slag worker, as illustrated in Table 3. The effective doses (ingestion, inhalation, external, collective, cumulative) for scrap working scenario are presented in Figures 1, 2 and 3, respectively. It is clear that at the scrap delivery stage the ingestion, inhalation and external dose are higher than code of conduct of IAEA by a factor of 6, where incidental ingestion of particulates attaches to the hands during cutting process. Workers inhale high dose in the scrap cutter and scrap loader and are exposed to a high external dose during truck driver. From Figure 2 it is obvious that for the smelter yard worker the ingestion dose and the inhalation dose were about 6.5µSv and 5.4 µSv respectively, which are about six times Code of Conduct IAEA limit [18]. The worker be inside the vicinity of smelting facility are exposed to radioactive air particulates. The inhalation dose for the smelter loader worker and furnance operator were about 27µSv and 37 µSv respectively. In Figure 3 the highest dose was for slag worker where the inhalation dose was about 0.2 mSv takes in 25 hours. Slag worker was also exposed to external of dose about 0.35 mSv. From the above results it turns out that slag worker is exposed to the highest dose in worker scenario. Table 4 and Figure 4 represent the fifths stages of the consumer scenario. It is noted that tool reuse and building reuse stages give high dose for ingestion, inhalation and external dose respectively, whereas public affected external dose is about 0.28mSv for 6 hours exposure when the slag is used in pavement. NRC and USDOE performance standards for both operational periods and the long-term protection of human health and the environment are fundamentally based on maximum allowable radiation dose levels, setting a maximum annual radiation dose to the public of 0.25 mSv [19].

The most effective dose was in the scrap product public scenario (building Reuse product) for ingestion and external of about 1.6 mSv and 1.4 mSv per year respectively. These results are within the range of agreement if they are compared with the results obtained using equation (2).

Table 2. *Effective dose equivalents (μSv) scrap delivery (working scenario).*

Scenario		**Effective dose Equivalents (μSv)**		**No of exposure people**
		DU	**IAEA**	
	Ingestion	1.04E+02	1.8E-1	
	Inhalation	4.04E+02	7.27E-1	
Scrap Cutter scenario	External	E+01.66 1	7.62 E+0	3
	Collective	1.53E-04	2.75E-6	
	Cumulative	1.53E-04	2.75E-6	
	Ingestion	1.46E+01	6.01E-2	
	Inhalation	0.45E+02	2.42E-1	
Scrap loader	External	2.28E+00	1.08E-2	2
	Collective	1.49E-04	6.27E-07	
	Cumulative	1.49E-04	6.27E +0	
	External	4.33E+00	9.68E-03	
Truck drive	Collective	2.33E-05	4.84E-08	4
	cumulative	2.33E-05	4.84E-08	
	Ingestion	4.71E+01	1.69E-01	
Scrap processor	Inhalation	4.08E+01	1.45 E-01	
	External	9.72E+00	7.69E-03	3
	Collective	5.45E-05	9.66E-07	
	comulative	5.45E-05	9.66E-07	
	Ingestion	6.47E+01	1.13E+00	
	Inhalation	5.39E+01	9.7E-01	
Smelter yard worker	External	3.34E+00	6.68E-02	10
	Collective	1.22E-03	2.16E-05	
	comulative	1.22E-03	2.16E-05	
	Ingestion	3.73E+00	6.49 E-02	
	Inhalation	2.69E+01	4.85E-01	
Smelter loder	External	1.2 9E+00	1.28 E-02	5
	Collective	1.56E-04	2.81E-06	
	comulative	1.56E-04	2.81E-06	
	Ingestion	4.67E+00	8.11E-02	
	Inhalation	3.37E+01	6.06E-01	
Furnance Operator	External	2.25E+00	4.61E-02	3
	Collective	1.22E-04	2.2E-06	
	Comulative	1.22E-04	2.2E-06	

Table 3. *Effective dose equivalents (μSv) scrap smelting (working scenario).*

Scenario		**Effective dose Equivalents (μSv)**		**No of exposure people**
		DU	**IAEA**	
	Ingestion	9.33E+00	1.62E-02	
	Inhalation	6.73E+01	1.21E-01	
Baghouse processor	External	1.02E+00	2.17E-03	1
	Collective	7.77E-05	1.4E-07	
	cumulative	7.77E-05	1.4E-07	
	Ingestion	4.67E+00	8.11E-02	
	Inhalation	3.37E+00	6.06E-01	
Refinery worker	External	0.00E+00	0.00E+00	3
	Collective	1.15E-04	2.06E-06	
	Cumulative	1.15E-04	2.06E-06	
	Ingestion	2.31E+02	4.02E+00	
	Inhalation	1.67E+03	3.00E+01	
Slag worker	External	3.46E+02	6.50E+00	1
	Collective	2.21E-04	4.05E-05	
	Comulative	2.21E-04	4.05E-05	

Table 4. *Effective dose equivalents (µSv) scrap product (public scenario).*

Scenario		Effective dose Equivalents (µSv)		No of exposure people
		DU	IAEA	
Public product pavement	External	2.83E+02	1.45E-01	820 E+04
	Collective	3.08E-01	1.47E-03	
	cumulative	3.07E+00	1.46E-02	
Reuse product (Tool reuse)	Ingestion	2.55E+02	4.43E+01	1
	Inhalation	1.77E+01	3.18E-01	
	External	1.78E+03	7.85E+00	
	Collective	2.80E-03	5.25E-05	
	cumulative	2.79E-02	5.25E-04	
Reuse product (Building reuse)	Ingestion	1.57E+03	4.46E+01	4
	Inhalation	1.02E+03	1.83E+01	
	External	1.42E+03	2.70E+01	
	Collective	1.75E-02	3.60E-04	
	Cumulative	5.24E-01	1.08E-02	

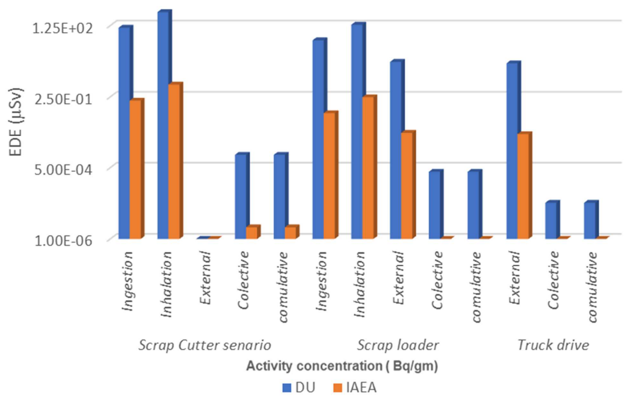

Figure 1. *Scrap delivery include (cutter- loader- Truck driver).*

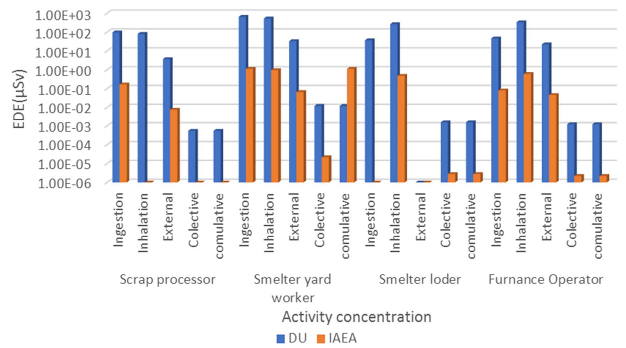

Figure 2. *Smelting scenario for Scrap processor-smelting yard –smelting loader and furnance operator stages.*

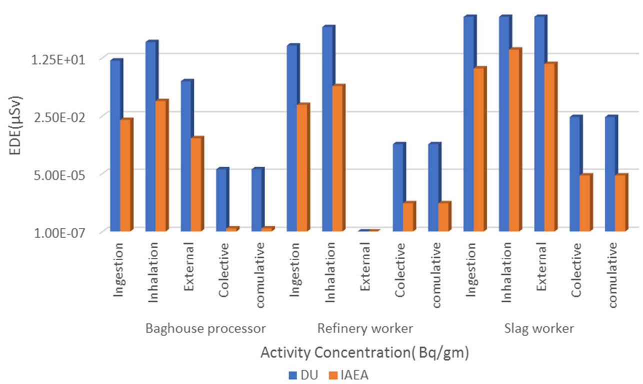

Figure 3. *Smelting processor for Bughouse – refinery and slag worker stages.*

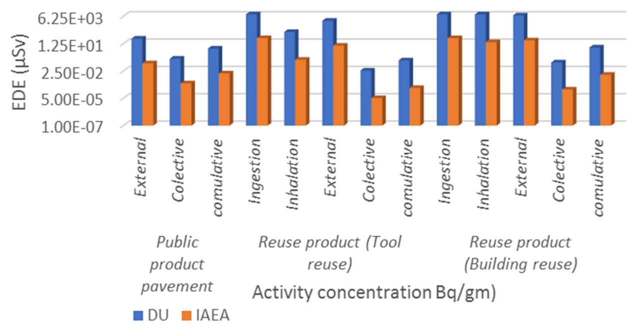

Figure 4. *Consumer scenario include–pavement –tool reuse and building reuse.*

4. Conclusion

Exposure effect of DU is mainly the result of its ingestion, inhalation where all uranium isotopes decay by alpha particles of various energies. Alpha particles have low penetrating power but deposit large amount of energy. Inhalation is the most likely route of intake of DU.

Public exposure to products incorporating radioactive scrap metal is most likely to result from external exposure. Melting radioactive source in metal recycle represent high hazard effect for slag worker, while for the public it is especially in tool reuse stage. Based on the zero-threshold linear dose response model, any absorbed dose of uranium is assumed to result in an increased risk of cancer. Since uranium tends to concentrate in specific locations in the body, the risk of cancer in the bone, liver, and blood (such as leukemia) may be increased [20].

Development of a worldwide recycling process will require further effort to determine the appropriate radioactivity limits for released materials to ensure protection of human health under possible conditions of exposure. It is important to provide the Scrap smelting places with ventilation machine, and special filtering equipment to protect workers from radioactive dust and particles that could be accidentally inhaled or ingested. All staff responsible for collecting, transporting and processing scrap metal should be provided with on-going training on the procedures in place in order to monitor for radiation and check for radioactive materials. Training should include how to recognize radiation symbols. Spreading safety, security and safeguard culture is requisite to reduce the hazards of radioactive materials.

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