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A Methodology For Estimating Potential Doses And Risks From Recycling U.S. Department Of Energy Radioactive Scrap Metals

by

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ABSTRACT: The U.S. Environmental Protection Agency (EPA) is considering writing regulations for the controlled use of materials originating from radioactively contaminated zones which may be recyclable. These materials include metals, such as steel (carbon and stainless), nickel, copper, aluminum and lead, from the decommissioning of federal, and non-federal facilities. To develop criteria for the release of such materials, a risk analysis of all potential exposure pathways should be conducted. These pathways include direct exposure to the recycled material by the public and workers, both individual and collective, as well as numerous other potential exposure pathways in the life of the material. EPA has developed a risk assessment methodology for estimating doses and risks associated with recycling radioactive scrap metals. This methodolgy was applied to metal belonging to the U.S. Department of Energy. This paper will discuss the draft EPA risk assessment methodology as a tool for estimating doses and risks from recycling.

INTRODUCTION

With the down-sizing of the United States' nuclear weapons program, and the closure of commercial nuclear power stations, large amounts of radioactively contaminated, or suspect, materials are expected to be generated. These materials may be comprised of old process equipment, piping, and structural metal and concrete, from the dismantlement of surplus buildings and structures in radioactively contaminated zones.

Materials originating in a controlled zone are generally treated as contaminated, until they can be declared "clean." Given the public sensitivity regarding radioactivity, however, the question "how clean is clean?" is especially problematic. The underlying question is how much risk, imposed or otherwise, is acceptable, and how is that level of risk determined?

EPA is now addressing the problem of management and disposition of wastes generated during site cleanup, including the demolition of buildings and structures. No national standards exist for the release and recycling of such materials containing residual levels of radioactive contamination. However, if some of these materials could be recycled, the burden on waste disposal facilities would be lessened.

EPA has performed a study for the U.S. Department of Energy (DOE) on the recycling of radioactive scrap metals (RSM) belonging to the DOE. These metals come mostly from the dismantlement of obsolete nuclear fuel facilities, weapons development and testing facilities, research facilities, and other operations where radioactive materials were used or processed. The study, titled "Analysis of the Potential Recycling of Department of Energy Radioactive Scrap Metal" (draft, September, 1994)[1], was undertaken to provide decision-making tools for DOE. A key component of the study is an assessment of the potential risks from recycling DOE's metal.

EPA developed a methodology for evaluating doses and risks from recycling RSM, and applied it to DOE RSM. If appropriate, EPA could further develop this recycling risk assessment methology for use in a future regulatory effort.

EPA RISK METHODOLOGY

Since no national standards exist for recycling radioactively contaminated materials, the EPA recycling study for DOE was constrained from making any implications as to what an appropriate recycling residual contamination level would be. Instead, the methodology is intended to be a tool for determining dose and risk for a set of scenarios by inputting the concentrations of the radionuclides in question for a quantity of metal. The study then estimated risks from the recycling of a specific quantity of DOE-owned steel with known radioactive contaminants. All data given are draft data.

The study focused on carbon and stainless steel. A recycling route for the steel was established, detailing the likely path that the metal would take from the scrap yard, through various recycling and manufacturing operations, to the hands of the consumer in the form of a product. Doses (effective dose equivalent) and risks were modeled at multiple points in the scrap route, up to the consumer who purchases a product.

All exposures to workers and the public come from the three products of the steel melting process: metal, slag, and offgas emissions. Radionuclides partition fairly consistently among these three phases. For example, most alpha-emitters partition thermochemically to the slag phase, while Co-60, Ni-63, and Tc-99 tend to stay in the molten metal. Others, such as Cs-137 and isotopes of polonium and lead, volatilize readily and must be captured in the offgas system. All major pathways were considered in each scenario, including:

* direct exposure (workers and public)
* inhalation of contaminated dust (workers)
* plume dispersion and consequent inhalation (workers and public)
* plume dispersion and consequent immersion (public)
* plume dispersion and consequent contaminated ground/soil leading to external exposure and food pathway (public)
* ingestion of contaminated water from run-off (public)
* ingestion of food contaminated with dust, or hand-to-mouth ingestion (workers)
* ingestion of food prepared in cook ware from recycled metal (public)

The scenarios chosen were judged to represent significant potential doses and risks, while still being probable. Scenarios, or operations, represent points in the process that include transportation workers, scrap yard workers, furnace operations and casting, bag house and slag pile workers, product manufacturing, and finished product users. (Table 3, at the end of this paper, shows a listing of all the scenarios/operations.) RSM decontamination operations were not modeled. These workers would be radiation workers and subject to DOE exposure limits and ALARA (as low as reasonably achievable) procedures.

All scrap metal in the study was assumed to be processed via melting in an 80 ton electric arc furnace (EAF), or a basic oxygen furnace (the EAF was considered to be more likely). Melting is an effective means of decontamination for many radionuclides, as well as producing an ingot or slab which is a feedstock for manufacturing. An EAF was assumed to operate continuously processing 110,000 MT of RSM in a year.

Initially, the modeling assumes a radionuclide concentration of 1 picocurie (37 mBq) per gram in metal for each radionuclide at each stage in the process. (The exceptions are airborne releases from the furnace, and concentrations in the slag.) This approach was chosen for the following reasons: the actual contamination in the scrap is not well characterized (with some exceptions); the melt decontamination partition coefficients are not precisely known; the results would not depend on the degree of dilution; and, doses and risks can easily be scaled up or down for a given scenario, depending on the actual radionuclide concentration.

Partition factors were used to determine the slag and offgas emission concentrations. For example, Am-241 goes 99% to the slag, with the remaining 1% left in the metal, while 90% of Mn-54 goes to the metal and 10% to the slag. Cs-137 varies from 0-50% going to the slag, and 50-100% to the offgas (100% was assumed to go to the offgas in the study).

Thus, doses and risks were assessed on a per picocurie per gram basis for 46 radionuclides (or 59, including separate calculations for those with short-lived progeny). The radionuclides considered are listed in Table 1.

Individual and population doses and risks per picocurie per gram were calculated for a total of 67 worker and consumer exposure scenarios (see Table 3 at the end of this paper for list of scenarios). One can then multiply the dose and risk values by any radionuclide concentration in metal to calculate the doses and risks for all applicable scenarios.

TABLE 1

Ac-228	Mn-54	Po-212	Sr-90	U-232	Pb-214+P
Am-241	Ni-63	Po-216	Tc-99	U-234	Po-216+P
Ba-137m	Np-237	Po-218	Th-228	U-235	Po-218+P
Bi-210	Pa-233	Pu-239	Th-229	U-236	Ru-106+P
Bi-212	Pa-234	Pu-241	Th-230	U-238	Sr-90+P
Bi-214	Pa-234m	Ra-224	Th-231	Y-90	Th-232+P
Co-58	Pb-210	Ra-226	Th-232	Cs-137+P	U-232+P
Co-60	Pb-212	Ra-228	Th-233	Np-237+P	U-235+P
Cs-134	Pb-214	Rh-106	Th-234	Pb-210+P	U-238+P
Cs-137	Po-210	Ru-106	Tl-208	Pb-212+P	

DOSE AND RISK CALCULATION

A number of computer codes were evaluated dealing with recycling and pathway analysis, including CONDOS[2] and IMPACTS-BRC[3], which treat recycling explicitly, but none were found entirely suitable for this analysis. Therefore, the modeling strategy was developed. The intent was to produce a methodology that would accurately evaluate the potential doses and risks, and be flexible enough to be applied to other recycling situations.

Each operation was represented by one or more spreadsheets using Microsoft EXCEL[4]. The EXCEL spreadsheet approach was chosen to take advantage of the program @RISK[5] to perform Monte Carlo uncertainty analyses along with the point estimates of dose and risk for each operation. Risks are presented as total lifetime cancer incidence risk per picocurie per gram per year of exposure.

The one exception to the EXCEL approach was the method used to estimate the means and uncertainties in the furnace emissions used to calculate individual and population exposures. An uncertainty method used in the development of the National Emission Standards for Hazardous Air Pollutants (NESHAPs[6]) regulation was used.

Table 2, below, gives sample input parameters for two worker exposure scenarios, and one consumer exposure scenario. Note that not all pathways factor in each scenario.

TABLE 2
Input Parameters for Selected Scenarios

a. Direct Exposure Pathway Calculation Input Parameters and Distributions

Scenario/Operation	Distance (m) distribution	min	most likely	max	value expected	Exposure (hrs/d) distribution	min	most likely	max	value expected
1.1.1.a Worker near a small scrap pile	uniform	1.0		20.0	10.5	triangular	1.0	4.0	8.0	4.3
6.2.1.a Exposure from EAF during melt	uniform	2.0		10.0	6.0	triangular	6.0	7.0	8.0	7.0
11.2.1.b End user of a large home appliance	triangular	0.3	0.3	1.0	0.5	triangular	1.0	1.5	2.0	1.5

Scenario/Operation	Exposure Period days/yr	years	hours	Number of Workers distribution	min	most likely	max	value expected
1.1.1.a Worker near a small scrap pile	250	1	1,083	triangular	1.0	3.0	5.0	3.0
6.2.1.a Exposure from EAF during melt	250	1	1,750	uniform	3.0		5.0	4.0
11.2.1.b End user of a large home appliance	350	1	525	uniform	1.0		1.0	1.0

TABLE 2, Cont'd

b. *Inhalation Exposure Pathway Calculation Input Parameters and Distributions*

Scenario/Operation	Respiratory Protection Reduction Factor				Dust Loading (g/m^3)				value
	Distribution	min	max	expected value	distrib.	min	likely	max	expected
1.1.1.a Worker near a small scrap pile	uniform	1	1	1	triangular	5.0E-4	5.0E-3	1.0E-2	5.17E-3
6.2.1.a Exposure from EAF during melt	uniform	1	1	1	triangular	5.0E-4	5.0E-3	1.0E-2	5.17E-3

Scenario/Operation	Exposure Periods			Number of Workers		most		value
	days/yr	years	hours	distribution	min	likely	max	expected
1.1.1.a Worker near a small scrap pile	250	1	1,083	triangular	1	3	5	3
6.2.1.a Exposure from EAF during melt	250	1	1,750	uniform	3		5	4

Scenario/Operation	Breathing Rate (m^3/hr)				Exposure Rate (hrs/d)				value
	distrib.	geo. mean	GSD	expected value	distrib.	min	likely	max	expected
1.1.1.a Worker near a small scrap pile	lognormal	1.83E-1	1.3	1.89E-1	triangular	1	4	8	4.3
6.2.1.a Exposure from EAF during melt	lognormal	1.83E-1	1.3	1.89E-1	triangular	6	7	8	7.0

c. Secondary Ingestion Exposure Pathway Calculation Input Parameters and Distributions

Scenario/Operation	CF for Fe in Fe_2O_3	Ingestion Rate gm/hr)				Exposure Rate (hrs/d)				value
		distribution	min	max	value expected	distrib.	min	max	likely	expected
1.1.1.a Worker near a small scrap pile	0.7	log-uniform	4.17E-7	4.17E-4	1.32E-5	triangular	0.5	1.0	1.5	1.0

Scenario/Operation	Exposure Periods			Number of Workers				value
	days/yr	years	hours	distrib.	min	likely	max	expected
1.1.1.a Worker near a small scrap pile	250	1	250	triangular	1	3	5	3

The computer code MICROSHIELD[7] was used to calculate dose conversion factors for external doses from all operations, for their particular geometry, at varying distances, and for each radionuclide. Dose and risk factors for other pathways were taken from published sources (see references 8-11). The doses and risks were calculated using standard dose/risk algorithms. For example, dose and risk from direct exposure are calculated as follows:

$$Dose_i\ (x)\ =\ C_{i,medium}\ *\ F_E(i,x)\ *\ t$$

$$Risk_i\ (x)\ =\ C_{i,medium}\ *\ F_{DR}\ *\ F_E(i,x)\ *\ t$$

where,

$\text{Dose}_i(x)$ = dose, 1 year exposure to radionuclide i; mrem/yr
$\text{Risk}_i(x)$ = total cancer incidence risk for 1 year of exposure to radionuclide i; risk/yr
$C_{i,\text{medium}}$ = concentration of radionuclide i in the medium of interest; pCi/g
$F_E(i,x)$ = dose factor relating exposure to dose for radionuclide i at distance x; mrem/hr per pCi/g
F_{DR} = risk factor relating dose to risk; total cancer incidence risk per mrem
i = radionuclide of interest
x = distance from source to receptor; meters
t = rate of exposure; hours per year

As already noted, estimates of dose and risk are based on a concentration of 1 pCi/g in metal for each radionuclide, for each scenario. The values in the dose/risk table generated in the report (hereafter called the DR Table) are used to estimate dose and risk once the true radionuclide concentrations are known.

This is a simple scaling procedure. For example, consider a batch of metal to be recycled that contains 12 pCi/g of Cs-137+P, and 15 pCi/g of Co-60, for the operation, "Worker near a small scrap pile (operation 1.1.1.a in Table 3)." From the DR Table, the estimates of dose and risk per picocurie per gram for an individual from these radionuclides are as follows:

Nuclide	Dose (mrem/yr)	Risk/year
Cs-137+P	3.2×10^{-3}	2.2×10^{-9}
Co-60	1.5×10^{-2}	1.0×10^{-8}

The dose to the worker would be,

$$12 \times 3.2\times10^{-3} + 15 \times 1.5\times10^{-2} = 0.26 \text{ mrem/yr}$$

and the risk would be,

$$12 \times 2.2\times10^{-9} + 15 \times 1.0\times10^{-8} = 1.8\times10^{-7} \text{ lifetime risk of}$$

cancer incidence per year of exposure.

The above calculation presumes all assumptions that went into producing the values in the DR Table are unchanged. Here, if desired, one can easily account for two of the assumptions. This worker scenario is based on five days per week of exposure to the pile. If the exposure time is reduced to one day per week, the above results need only be divided by 5. This scenario also assumes the pile is 100% RSM. If the pile is only 50% RSM, and the rest is "clean" scrap (evenly distributed), the initial results need only be divided by 2.

Each dose and risk value in the DR Table is a sum of dose and risk for each applicable pathway. The methodology affords certain parameters in the scenarios to be easily varied to estimate doses and risks with different inputs. For example, the "Worker near a small scrap pile" consists of direct exposure, inhalation and secondary ingestion pathways. One can vary exposure parameters for each pathway.

The concentration in the slag and offgas, however, is not taken to be 1 pCi/g as it is in the metal. To obtain the concentration in the slag and offgas dust, partition and concentration factors are applied to the scrap metal radionuclide concentration.

Some modifications must be made to estimate population doses and risks from consumer products. Since it is not known how many people will use a consumer product, the population doses and risks were calculated per curie of radioactivity in the metal used to make that product (curie values are for melted metal). The population of product users need not be known to calculate these values - the values represent dose and risk spread over a group of individuals. If some of the scrap is used for making kitchen cook ware, and some for large appliances, the total activity must be adjusted for the fraction going to each use.

The impact on the population, then, is the number of cancers that would be expected. For example, in the DR Table, the large home appliance scenario (Table 3, #11.2.1b) gives a population risk of 0.66 per curie from Co-60. If the population exposed is 1000 persons from 1000 appliances with a total of one curie of Co-60 in them, the effects would be 0.66 cancers in the population of 1000 (given the parameters of the scenario). If one curie is divided into 100,000 appliances with 100,000 users, the effects would be 0.66 cancers in that population.

DOSE AND RISK FROM DOE's STEEL

EPA evaluated doses and risks for 5 options presumed to represent what DOE could do with its RSM. The options evaluated are: No Action, or keeping the metal in piles or storage; Safe Storage, which allows for improved storage of the RSM and delayed disposal; Disposal, which entails immediate shipment to a waste facility; Restricted Recycling, which would allow the metal to be recycled and fabricated into uses within the DOE or nuclear industry; and, Unrestricted Release, which could result in consumer products being made with recycled RSM.

In the study, an existing quantity of RSM at the Oak Ridge Reservation in Oak Ridge, Tennessee, which is a candidate for recycling, was used to estimate potential risks from recycling

DOE steel. A total of 60,000 metric tons of steel currently exists at Oak Ridge. The Oak Ridge metal has been fairly well characterized, including its radioactive contamination. The analysis is, therefore, specific to this particular quantity, its location, and suite of radioactive contaminants, and does not necessarily characterize risks from all DOE RSM. The measured contaminants are:

Radionuclide	Concentration in Metal	
U-238	600 pCi/g	(22 Bq/g)
Tc-99	85,000 pCi/g	(3,160 Bq/g)
Np-237+P	0.035 pCi/g	(0.0013 Bq/g)
Pu-239	0.30 pCi/g	(0.011 Bq/g)

The estimates of dose and risk are based on the DR Table containing dose and risk per picocurie per gram, adjusted to account for the actual concentrations of the radionuclides found in the Oak Ridge metal. To obtain the concentrations of the four radionuclides in each melt phase, they were given the following partition factors (note that no fraction of these radionuclides partitions to the offgas):

Radionuclide	Metal	Offgas/dust	Slag
U-238	0.01	0	0.99
Tc-99	1.0	0	0
Np-237+P	0.01	0	0.99
Pu-239	0.01	0	0.99

After melting and decontamination, dose and risk factors from the DR Table were multiplied by the resultant concentrations of the four radionuclides, given below, and summed to estimate the doses and risks in the various scenarios involved in each DOE option.

Radionuclide	Resultant Concentration - Metal	
U-238	6 pCi/g	(0.22 Bq/g)
Tc-99	85,000 pCi/g	(3,160 Bq/g)
Np-237+P	3.5×10^{-4} pCi/g	(1.3×10^{-5} Bq/g)
Pu-239	0.003 pCi/g	(1.1×10^{-4} Bq/g)

Worker and public exposure scenarios were adjusted to accommodate the specific parameters for the Oak Ridge metal recycling options. For example, the Disposal option involves shipping 60,000 MT of RSM from Oak Ridge, TN, to a waste facility in Nevada (3,200 km). Worker and population doses were calculated according to the number of shipments, the number of workers necessary, and the population that would be exposed during the shipments.

The individual and population doses and risks for each scenario from recycling 60,000 MT currently retained at the Oak Ridge Reservation are listed in Table 3 at the end of this paper. In the restricted recycling option, all the sceanrios would presumably occur except that no metal would be made into consumer products. In the unrestricted recycling option, all the scenarios would presumably occur.

Population risk from products made with the recycled metal must also adjusted for the quantity of metal recycled. The population risk depends on the total curies of each radionuclide that is recycled. Thus, the doses and risks for scenarios were multiplied by the mass of metal (60,000 MT), and the concentration of each radionuclide (given the above partitioning), and then summed over the four radionuclides. Population doses and risks for the end product scenarios are also a function of the fraction of the total quantity given to each product. Therefore, a value must be given describing what percentage of the RSM may be used for each product, and multiplied by the dose and risk. For example, if 50% of the metal is presumed to go into automobiles, and 50% into appliances, then the dose and risk for the automobile and appliance scenarios are each divided by two.

LIMITATIONS

One limitation of this methodology is that only the scenarios given can be modeled. New scenarios can be developed, but they are time consuming to research and generate. Also, some parameters of these scenarios are not easy to change, resulting in inflexibility in the use of the scenario: for example, doubling the EAF size from 80 tons to 160 tons will not result in twice the emissions, nor will it lead to twice the dose to the furnace worker. To truly evaluate the risks from RSM recycling, a more comprehensive analysis of the most appropriate and representative scenarios should be done.

It should also be noted that many of the scenarios have large uncertainties. For many scenario parameters, the mean value and probability distribution are not known. In some cases, the distributions reflect the subjective judgement of the analysts, and are not based on subjective evidence. Others have large inherent uncertainties, for example, scenarios which require breathing rates as a factor, and those requiring dust settling velocities, will have large uncertainties associated with them.

CONCLUSIONS

The EPA has completed a draft study of recycling radioactively contaminated scrap metal to provide information and decision-making tools for the U.S. Department of Energy. A key component of the study is a methodology for assessing doses and risks which may result from the recycling of DOE-owned steel.

The methodology is based on picocurie per gram dose and risk factors calculated for each radionuclide considered for one year of exposure. Individual and population risk factors for a wide range of worker and public exposure scenarios attempt to characterize the potential doses and risks that could be received if metal containing residual radiation were recycled. This methodology was then applied to a specific quantity of DOE-owned steel with known radioactive contamination, to estimate the doses and risks that could result.

The methodology affords flexibility in modeling recycling situations. The modeler only needs to know the starting quantity of metal and the nature of the contamination to estimate individual and population doses and risks for the given scenarios. Some of the parameters in the exposure scenarios can be easily modified to accommodate specific exposure situations to which the model is applied.

Additional work that is needed on the risk assessment methodology includes the development of more exposure scenarios, and improving on uncertainties. This modeling methodology should be evaluated for its usefulness in any regulatory development process concerning residual radioactivity in recycled materials.

Table 3. Annual Doses and Risks from Recycling 60,000 MT of Scrap Metal

Starting Concentrations, pCi/gm

U-238 5.99E+02 TC-99 8.52E+04 NP-237+P 3.51E-02 PU-239 2.97E-01

OPERATION	*INDIV.* DOSE	*INDIV.* RISK	*POP.* DOSE	*POP.* RISK
1.1.1a Working near small (25 ton) scrap pile	3.29E+02	6.42E-05	9.88E-01	1.93E-04
1.1.1b Working near large (250 ton) scrap pile	3.29E+02	6.42E-05	9.88E-01	1.93E-04
2.1.1a Loading /Unloading from small (25 ton) scrap pile	3.29E+02	6.42E-05	9.88E-01	1.93E-04
2.1.1b Loading /Unloading from large (250 ton) scrap pile	3.29E+02	6.42E-05	9.88E-01	1.93E-04
2.1.2a Driver: Beside vehicle	5.69E-05	4.04E-11	5.69E-08	4.04E-11
2.1.2b Driver: Inside cab of vehicle	4.32E-04	3.07E-10	4.32E-07	3.07E-10
2.2.1 Population: Truck transporting scrap	0.00	0.00	6.84E-05	4.88E-08
4.1.1a Unloading the truck - small (25 ton) scrap pile	1.24E-04	8.81E-11	2.49E-07	1.77E-10
4.1.1b Unloading the truck - large (250 ton) scrap pile	3.69E-04	2.61E-10	7.34E-07	5.23E-10
4.1.2 Working around 1,500 ton scrap pile	3.29E+02	6.42E-05	1.32E+00	2.57E-04
4.1.3 Cutting/sizing scrap for furnace charge	1.56E+02	3.05E-05	4.67E-01	9.19E-05
5.1.1 Loading /Unloading truck	1.70E-05	1.20E-11	5.09E-08	3.62E-11
5.1.2a Driver: Beside vehicle	4.14E-05	2.96E-11	4.14E-08	2.96E-11
5.1.2b Driver: Inside cab of vehicle	3.72E-04	2.65E-10	3.72E-07	2.65E-10
5.2.1 Population: Truck transporting processed scrap	0.00	0.00	1.04E-04	7.41E-08
6.1.1a Exposure from scrap pile	5.31E+02	1.04E-04	7.94E-01	1.56E-04
6.1.1b Exposure from moving the scrap by magnet	5.31E+02	1.04E-04	7.94E-01	1.56E-04
6.1.1c Exposure from moving the scrap by small charging bucket	5.31E+02	1.04E-04	7.94E-01	1.56E-04
6.1.1d Exposure from moving the scrap by large charging bucket	5.31E+02	1.04E-04	7.94E-01	1.56E-04

Starting Concentrations, pCi/gm

U-238 5.99E+02 TC-99 8.52E+04 NP-237+P 3.51E-02 PU-239 2.97E-01

OPERATION	INDIV. DOSE	INDIV. RISK	POP. DOSE	POP. RISK
6.1.2a Exposure from EAF during melt	7.58E+02	1.48E-04	3.03E+00	5.95E-04
6.1.2b Exposure from BOF during melt	7.58E+02	1.48E-04	3.03E+00	5.95E-04
6.1.3a EAF - Exposure to molten steel in ladle	5.59E-04	2.36E-10	2.24E-06	9.48E-10
6.1.3b EAF - Exposure to molten slag in ladle	1.69E-02	1.09E-09	6.80E-05	4.34E-09
6.1.3c BOF - Exposure to molten steel in ladle	5.66E-04	2.42E-10	2.27E-06	9.69E-10
6.1.3d BOF - Exposure to molten slag in ladle	1.71E-02	1.20E-09	6.86E-05	4.80E-09
6.2.1a Population: Exposure to emissions from EAF	0.00	0.00	0.00	0.00
6.2.1b Population: Exposure to emissions from BOF	0.00	0.00	0.00	0.00
7.1.1 Exposure from molten steel in tundish	3.17E-07	2.25E-13	1.59E-09	1.13E-12
7.1.2 Exposure from continuous caster	1.50E+01	8.43E-06	4.50E-02	2.53E-05
7.1.3a Standing near 10-ton ingots	1.37E-06	9.76E-13	5.48E-09	3.90E-12
7.1.3b Standing near 1-ton ingot	*2.52E-07*	*1.79E-13*	*1.01E-09*	*7.16E-13*
7.1.3c Standing near slabs	1.41E-05	1.00E-11	5.65E-08	4.04E-11
7.1.3d Standing near coils	1.56E-05	1.11E-11	6.25E-08	4.46E-11
8.1.1 Handling the bag house filters	2.66E+00	5.20E-07	1.33E-02	2.60E-06
8.1.2a Transporting baghouse dust for disposal - side of vehicle	4.74E-04	3.37E-10	7.13E-07	5.05E-10
8.1.2b Transporting baghouse dust for disposal - cab of vehicle	1.38E-04	9.79E-11	2.06E-07	1.47E-10
8.2.1 Population: Truck transporting baghouse dust	0.00	0.00	2.43E-07	1.73E-10
9.1.1 Exposure to slag pile at slag processor	4.13E+04	7.79E-03	1.65E+02	3.12E-02

Starting Concentrations, pCi/gm

U-238 5.99E+02 TC-99 8.52E+04 NP-237+P 3.51E-02 PU-239 2.97E-01

OPERATION	INDIV. DOSE	INDIV. RISK	POP. DOSE	POP. RISK
9.1.2 Exposure from use of slag in road construction	4.13E+04	7.79E-03	3.72E+02	7.01E-02
9.2.1 Population: Truck transporting slag for disposal	0.00	0.00	2.39E-05	1.70E-08
9.2.2 Population: Exposure from use of slag in road construction	2.76E-04	1.96E-10	3.31E-04	2.35E-07
9.2.3 Population: Ingestion of water contaminated by slag pile	0.00	0.00	1.40E+02	3.19E-06
10.1.1a Manufacturing cars	2.37E-06	1.68E-12	9.48E-09	6.74E-12
10.1.1b Manufacturing large home appliance	2.70E-06	1.92E-12	1.08E-08	7.65E-12
10.1.1c Manufacturing large industrial equipment	4.67E-06	3.31E-12	1.86E-08	1.32E-11
10.1.1d Manufacturing eye glasses	3.86E-07	2.73E-13	1.54E-09	1.09E-12
10.1.1e Manufacturing pans	6.56E-06	4.67E-12	2.63E-08	1.87E-11
10.1.2a Distribution of cars	7.65E-06	5.44E-12	7.65E-09	5.44E-12
10.1.2b Distribution of large home appliance	8.11E-06	5.76E-12	8.11E-09	5.76E-12
10.1.2d Distribution of eye glasses	3.58E-07	2.55E-13	3.58E-10	2.55E-13
10.1.4a Point of sale of car	5.93E-07	4.21E-13	5.93E-10	4.21E-13
10.1.4b Point of sale of large home appliances	4.07E-07	2.90E-13	4.07E-10	2.90E-13
10.1.4d Point of sale of eye glasses	7.79E-07	5.55E-13	7.79E-10	5.55E-13
10.1.4e Point of sale of pans	1.17E-06	8.28E-13	1.17E-09	8.28E-13
10.2.1a Population: Truck transporting cars	0.00	0.00	5.12E-08	3.65E-11
10.2.1b Population: Truck transporting large home appliances	0.00	0.00	7.93E-09	5.62E-12
10.2.1c Population: Truck transporting large industrial equipment	0.00	0.00	9.27E-09	6.60E-12

Starting Concentrations, pCi/gm

U-238 5.99E+02 TC-99 8.52E+04 NP-237+P 3.51E-02 PU-239 2.97E-01

OPERATION	INDIV. DOSE	INDIV. RISK	POP. DOSE	POP. RISK
10.2.1d Population: Truck transporting eye glasses	0.00	0.00	2.54E-09	1.81E-12
10.2.1e Population: Truck transporting pans	0.00	0.00	9.41E-09	6.67E-12
11.2.1a Population: End user of a car	3.65E-06	2.59E-12	1.36E-03	9.69E-07
11.2.1b Population: End user of a large home appliance	3.28E-06	2.33E-12	1.51E-03	1.08E-06
11.2.1c Population: End user of large industrial equipment	6.14E-06	4.35E-12	4.97E-05	3.53E-08
11.2.1d Population: End user of eye glasses	1.25E-05	8.88E-12	6.56E+01	4.66E-02
11.2.2a Population: Fe from iron utensils	4.76E+00	4.02E-06	4.16E-03	2.94E-06
11.2.2b Population: Fe from stainless steel	1.85E-02	1.55E-08	4.16E-03	2.94E-06
11.2.2c Population: Ni from stainless steel	4.76E-02	4.02E-08	4.16E-03	2.94E-06
11.2.2d Population: Al from aluminum utensils	9.53E-03	8.02E-09	4.16E-03	2.94E-06

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