APPENDIX E
MISCELLANEOUS DOSE TOPICS

This appendix discusses the following dose topics:

- The dose assessment analysis in NUREG-1640 and a comparison of those results to international guidance.
- Sources and typical annual doses from background radiation.
- Collective dose due to background radiation.
- Exposures from multiple sources derived from the release of materials from licensees.

E-I RADIOLOGICAL ASSESSMENTS FOR THE RELEASE OF MATERIALS, INCLUDING COMPARISON OF NUREG-1640 RESULTS WITH INTERNATIONAL GUIDANCE

1. INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) has independently assessed potential doses to individuals that could result from the release of solid materials, with the results expressed as normalized activity levels, as Bq/g and Bq/cm^2. The analyses were conducted for ferrous metals, copper, aluminum, and concrete, with the results reported in NUREG-1640 (NRC 2003d). One of the main objectives of these assessments was to identify the critical group and quantify the mean dose to that group using realistic exposure scenarios. Normalized dose factors were calculated for 115 radionuclides and for each material. These assessments are intended to be supporting of the technical basis for a rulemaking on controlling the disposition of solid materials. The design objectives, the analytical approach, and results of the analyses were compared to guidance from the European Commission (EC) and International Atomic Energy Agency (IAEA). The results of these comparisons are briefly described below.

2. DESIGN OBJECTIVES FOR ANALYSES AND ANALYTICAL APPROACH IN NUREG-1640

The establishment of design objectives for the dose assessment analysis were defined at the beginning of the process, provided the basis for numerous decisions in structuring calculations and the means for narrowing down the scope of evaluations in selecting appropriate input parameters.

2.1 Design Objectives

The design objectives of estimating potential doses to individuals arising from the release of materials included independent assessments of U.S. industry practices in a realistic, i.e., non-conservative, approach, that takes into account, to the extent practicable, variations in industrial practices. The results of such assessments could be used as part of a technical basis in a rulemaking on controlling the disposition of solid materials, taking into account public comments received on earlier proposed regulations. Regarding implementation, results for both mass-based and surface-based release levels were considered in the overall objective. Moreover, comparisons with existing U.S. regulations, guidance, and practices, along with international clearance guidance, were considered in the design objective in calculating radionuclide concentrations using ICRP 30 (ICRP 1979) and ICRP 60 (ICRP 1991) based dosimetry (ICRP 1975, 1979, 1990, 1994). Overriding design objectives were to identify the critical group for generic release levels and to quantify that group's mean potential dose on a normalized unit concentration basis. Because materials released from a nuclear facility may be characterized by a wide spectrum of radionuclides, the assessments consider exposures from direct radiation, inhalation, and ingestion to adults making up the critical group for each scenario. Thus, it was not a design objective to assess doses to infants and children or to the skin.

Another design objective was to build into the structure of the analyses breadth of scenarios, robustness, and adaptability, so that the licensees could use the generic analyses to support case-specific analyses.

2.2 Analytical Approaches

In general the analytical approaches were guided by the design objectives. Key approaches that characterize these assessments are described below.

2.2.1 Probabilistic analysis

A probabilistic analysis approach was adopted for several reasons. It enables one to take into account variations in input parameters encountered in real situations from which mean values and uncertainties can be estimated. The mean values were considered the most appropriate estimators of normalized dose to an individual for each scenario. The means were ranked to identify the critical groups on a radionuclide-by-radionuclide basis. Ferrous metals, copper, aluminum, and concrete were specifically analyzed because these materials were judged to comprise the great majority of mass likely to be candidate materials for release.

For the various possible pathways considered, realistic choices for their parameters were evaluated using a Monte Carlo statistical averaging technique. The results provide estimates of the collective dose average values and associated uncertainties. Distributions of variable parameters were established based on the quality of the data using literature research for the identified variables (EPA 1994). The ranges of parameters were kept realistic, and were often found to be as uniform, triangular, or beta distributions. The estimation of doses, radionuclide concentrations, or other intermediate parameters involved between 5,800 and 10,000 realizations or calculations, with each set of results forming a probability distribution. The mean values and the 5^{th}, 50^{th}, 90^{th}, and 95^{th} percentile values of each distribution are listed in NUREG-1640 (NRC 2003d). In all cases where an intermediate parameter is calculated using Monte Carlo sampling methods, each of the calculated values is used as input to the next step in the calculation. For example, in using 10,000 realizations to estimate a dose, each realization uses each of 10,000 radionuclide concentrations in succession. Calculations were performed with spreadsheets using commercially available software.

2.2.2 Radionuclides

A total of 115 radionuclides were included in the analysis based on an evaluation of the nuclear industry. In general, the radionuclides correspond to those reported in low-level radioactive waste from a broad variety of facilities, in studies of radionuclide inventories found at nuclear power reactors, neutron activation products, radioactive decay progenies, and those listed in the EC publication Radiation Protection 89 (RP 89) (European Commission 2000a).

2.2.3 Chemical forms and particle sizes

In order to meet the design objective of realistic dose assessments, each scenario was analyzed to determine the most likely chemical form and particle size distributions in the medium of concern and scenario. The appropriate corresponding dose conversion factors or dose coefficients were then used for that calculation.

2.2.4 Assessment of radionuclides on the surface

The critical parameter for assessing the potential doses from radionuclides on the surface of released materials is the mass-to-surface ratio, which is defined as the mass of the component divided by the exposed surface area of that component. Mathematical distributions of mass-to-surface ratios were developed from data derived from site visits and from reports on metal scraps likely to be released from commercial nuclear power plants undergoing dismantlement. Rebar, structural steel, and pipe hangers account for most of the mass of ferrous metals likely to be a candidate for release. Similar distributions were developed for copper and aluminum. For concrete, distributions were developed similarly, however, due to the considerable wall thicknesses found at nuclear facilities - especially nuclear power plants - the mean ratio is significantly higher, namely, 280 g/cm^2 compared to 5 g/cm^2 for ferrous metals. Values from the appropriate mass-to-surface ratio distribution were selected at random during the Monte Carlo analysis and divided into the mass-based normalized dose factor to yield the surficial normalized dose. The distributions of the radionuclides were considered to be uniform over all surfaces. In many cases, this assumption leads to an unrealistic overestimate; however, the situations vary so greatly that a generic analysis was judged not feasible. Therefore, if a less conservative assessment were desired, case-specific factors would have to be taken into account.

2.2.5 Scenario selection

Scenarios were generally selected as realistic candidates to identify the critical group. Some scenarios were selected for analysis because there had been questions raised in public meetings concerning the potential exposures associated with them - especially for consumer products. A third category of scenarios was developed to assess bounding cases where scrap in a single melt was entirely composed of released metal scraps. A significant amount of research was conducted to ensure that the models reflected current U.S. practices for handling scrap metals and concrete for reuse. Because metal refining processes can cause radionuclides to partition to by-products, scenarios covered not only scrap, but also refined metal, slag or dross, dust, airborne emissions, and drinking water downstream from a landfill, among others. In all, eighty-six scenarios were analyzed among the four materials.

2.2.6 Partitioning of radionuclides in refining processes

The distribution of impurities during melting and refining of ferrous metals can be influenced by numerous physical and chemical factors. The partitioning of radionuclides was determined by a combination of considerations. Generally, thermodynamic calculations were used to determine whether an element was likely to partition to the slag or to the melt. Vapor pressures of the more volatile elements and their oxides were used to predict concentration in the dust. These theoretical considerations were supplemented with a review of the literature to obtain realistic data. The convention was adopted that, if an element tends to remain in the melt, 1% is assumed to be physically entrained and transported to the dust due to the turbulence of the melting and refining processes. Similarly, if an element tends to partition to the slag, 5% is assumed to be transported to the dust. Detailed discussions and references are presented in the appendices to NUREG-1640.

3. RESULTS AND COMPARISONS

Detailed probabilistic results are presented in NUREG-1640 for each scenario and each material. In the discussions that follow, the means of the effective dose realizations were used to determine the critical group and for comparison with EC and IAEA guidance. It should be noted that these comparisons address normalized dose factors to individuals within critical population groups, and should not be confused with collective dose, which is the focus of Chapter 3 of the Draft GEIS. Collective doses to a population are used to compare the relative impacts of alternatives.

3.1 Results

For ferrous metals, most critical groups are workers, for example processing either scrap metals or melt products. The use of consumer products containing ferrous metals does not rise to a threshold at which exposures to a specific critical group might be limiting. Other critical groups are controlling for a very few radionuclides associated with exposures from atmospheric releases or drinking water. The scenarios and doses of scrap metal handlers and processors cover the majority of radionuclides and are controlling in defining release levels.

The overall critical groups, on a radionuclide basis, were defined by scenarios for the release of ferrous metals and concrete. These scenarios were almost all from workplace exposures. Thus, controlling hypothetical doses to workers would also control the hypothetical doses to consumers, and would result in lower doses to consumers. Figure E-1 shows the critical group scenarios for ferrous metals and the number of radionuclides for which that scenario defines the critical group. Electric arc furnace is abbreviated as EAF in the scenario descriptions.

Figure E-2 shows the critical group scenarios for concrete. In the scenario description, a municipal solid waste (MSW) landfill with leachates refers to drinking water from a well down-gradient or an industrial landfill where the leachates have reached ground water. One-thousand years after disposal was arbitrarily selected as a time interval when considering ingestion of ground water.

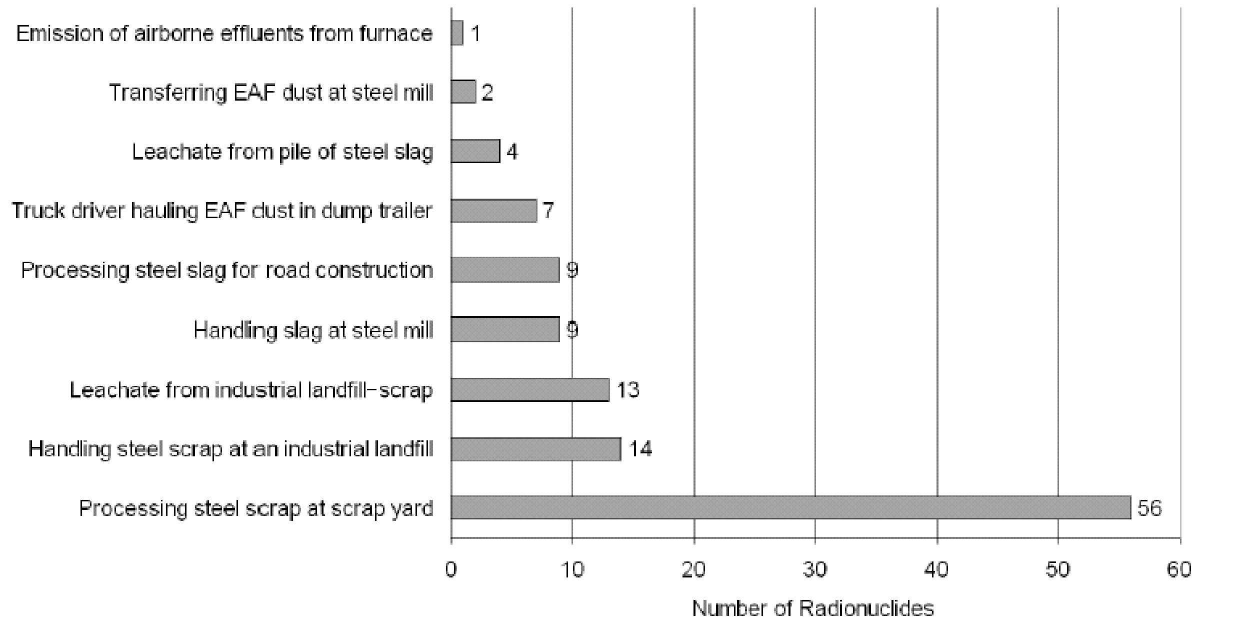

Figure E-1 Critical Group Exposure Scenarios and Defining Number of Radionuclides for the Release of Ferrous Metals

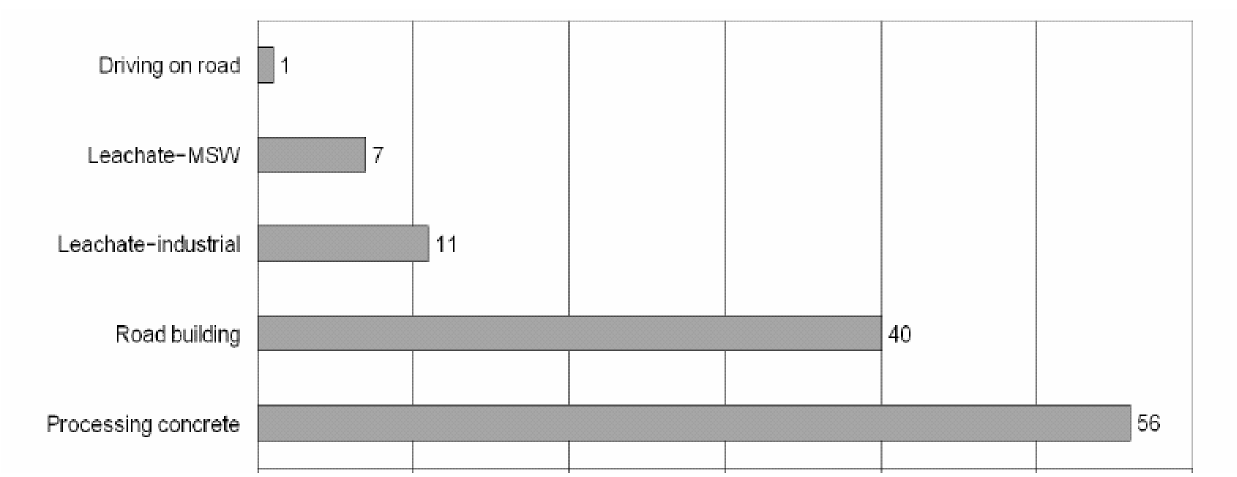

Figure E-2 Critical Group Exposure Scenarios and Defining Number of Radionuclides for the Release of Concrete

3.2 Comparisons

Figure E-3 presents a comparative scatter-plot of effective dose factors from NUREG-1640 on a 10 μSv (1 mrem) in a year basis using the values from EC Radiation Protection 122 (RP 122) (European Commission 2000b). The results are presented in order of increasing radionuclide atomic weight, from tritium to Cf-252. On a radionuclide-by-radionuclide basis, the NUREG-1640 most restrictive (overall critical group) results were divided by the RP 122 values. Thus, when the ratios are greater than one, the NUREG-1640 values are less restrictive than the RP 122 values. Most of the calculations comparing NUREG-1640 with the EC's RP 122 are within a factor of ten of one another.

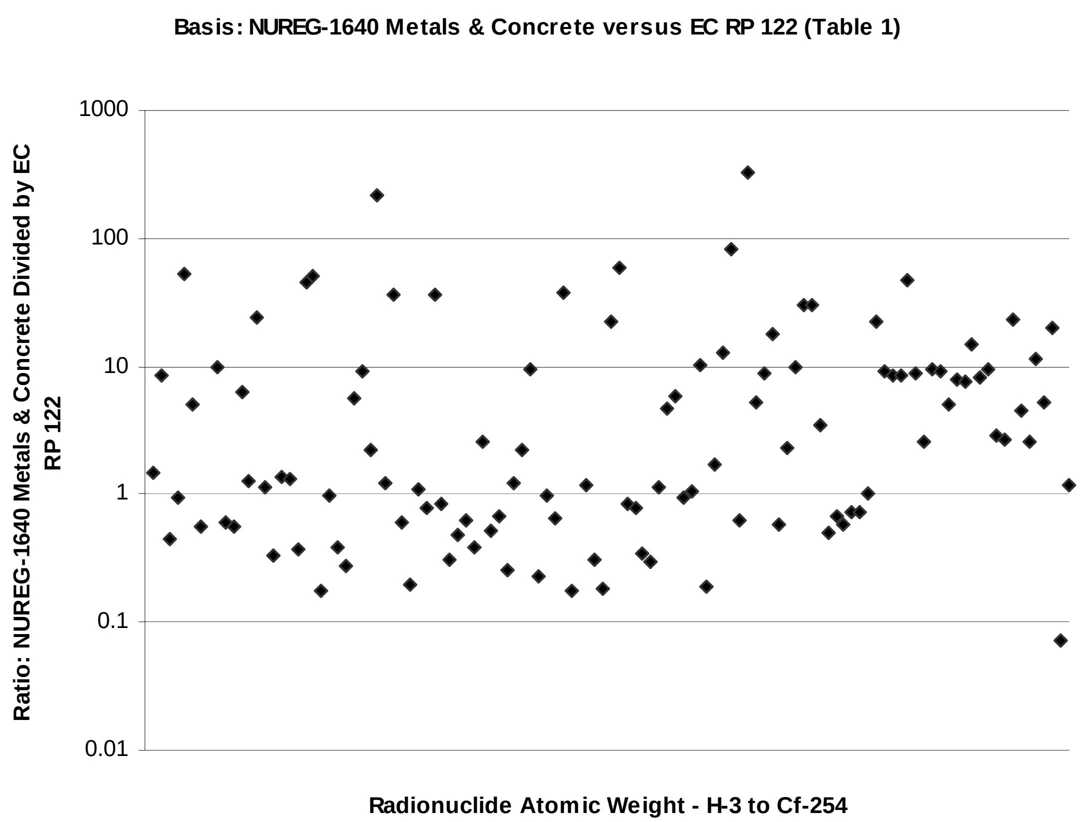

Figure E-3 Radionuclide-by-Radionuclide Comparisons of Values from NUREG-1640 to EC RP 122.

Figure E-4 illustrates a similar comparison with the guidance in the EC's RP 89, which is limited to the recycling of metals from the dismantling of nuclear installations (European Commission 2000a). For this comparison, the NUREG-1640 results for concrete were not included, and the effective dose calculations were used to have a consistent dosimetry system. Most of the results are within a factor of three on a radionuclide-by-radionuclide basis. Only four of the results from EC RP 89 are more restrictive by a factor greater than ten. The differences in the results would require a more detailed evaluation and comparison of the models and assumptions, and could partially reflect a different characterization of industrial practices.

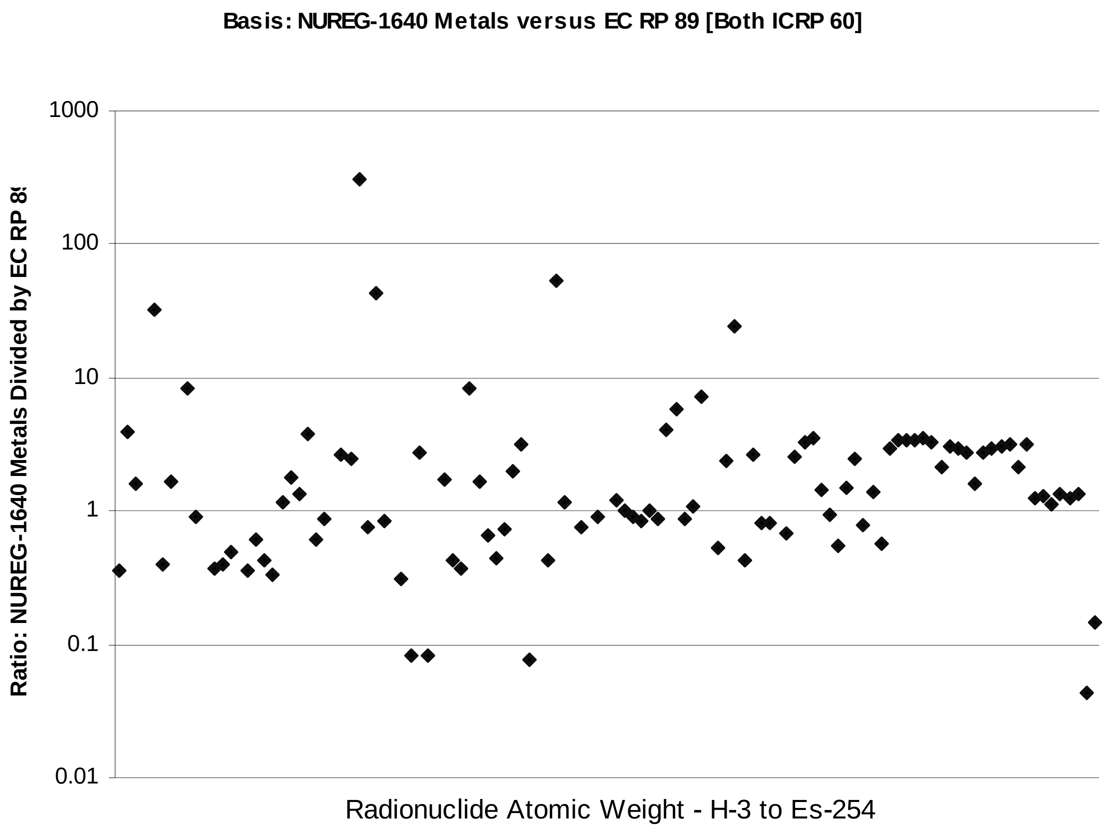

Figure E-4 Radionuclide-by-Radionuclide Comparisons of Values from NUREG-1640 to EC RP 89

Figure E-5 presents a comparative display of the results between NUREG-1640 and IAEA Radiation Safety Guide No. RS-G-1.7 clearance levels (IAEA 2004). The IAEA clearance levels are based on a 10 µSv in a year dose limit. For NUREG-1640, values used in the comparison are based on the most restrictive (overall critical group). The NUREG-1640 results were divided by the corresponding IAEA radionuclide values. As before, when ratios are greater than one, the NUREG-1640 values are less restrictive than the IAEA values. Most of the ratios between NUREG-1640 and IAEA are within a factor of ten of one another.

Most of the calculations comparing NUREG-1640 with the EC's RP 122 or IAEA's RS-G-1.7 guidance are within a factor of ten of one another. For those radionuclides where ratios are greater than one, RP-122 or RS-G-1.7 is more restrictive than NUREG-1640. Generally, ratios less than ten are considered good agreement by modelers because of the uncertainties in making such estimates taking into account, to the extent practicable, variations in modelling complex industrial processes. In part, the variability is attributed to differences in code models; scenarios and exposure pathways describing industrial practices; assumptions and parameters; incorporation of radon and its decay products; adjustments of EC and IAEA clearance values with that of other exemptions to ensure compatibility; and process used in rounding of RP 122 and IAEA values to the nearest power of ten.

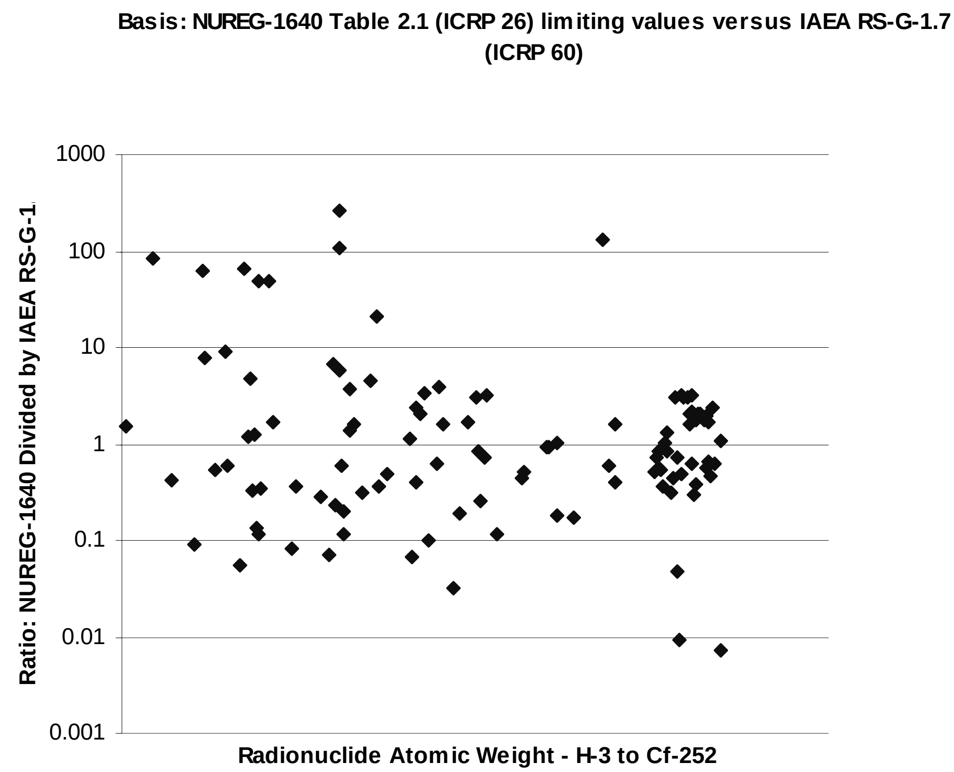

Figure E-5 Radionuclide-by-Radionuclide Comparisons of Values from NUREG-1640 to IAEA RS-G-1.7

The consequence of erring by a factor of ten, with a release criterion based on a 10 µSv (1 mrem) per year dose limit, could mean that a hypothetical individual might receive a dose of 100 µSv (10 mrem) in a year, which is a small fraction of the 1,000 µSv (100 mrem) per year dose limit that is considered protective of public health and safety (see 10 CFR Part 20, Subpart D - Radiation Dose Limits for Individual Members of the Public).

The above discussions addressed comparisons of individual radionuclides, but in implementation, two or more radionuclides may be present in materials that may be released. In such instances, the dose contribution of each radionuclide must be accounted for such that the total dose due to all radionuclides does not exceed the release criteria. This consideration is a requirement of NRC regulations in applying the sum-of-the-ratio. The sum of the ratios of each radionuclide present in materials cannot exceed unity when summed up over all radionuclides, i.e., unity rule. The ratio for a radionuclide is expressed as the concentration of that radionuclide divided by its limit. An example is used to compare differences between NUREG-1640 and RS-G-1.7 release levels when multiple radionuclides are present. The example considers radionuclides and their relative fractions for those radionuclides commonly found in materials generated by nuclear power plants. Typically, 17 radionuclides make up most of the residual activity expected to be found in materials subjected to release, with Fe-55, Co-60, and Cs-137 comprising nearly 80% of the total activity. The following tabulation presents the results of the comparison using the unity rule for all 17 radionuclides.

Case	Concrete	Ferrous Metals
RS-G-1.7 residual gross activity concentration, Bq/g (pCi/g)	0.14 (3.8)	0.14 (3.8)
NUREG-1640 residual gross activity concentration, Bq/g (pCi/g)	0.063 (1.7)	0.34 (9.1)
Ratio of residual concentrations (RS-G-1.7 ÷ NUREG-1640)	2.3	0.4
Restrictive case	NUREG-1640	RS-G-1.7

The results reveal that NUREG-1640 and RS-G-1.7 are alternatively more limiting depending on the type of material. For concrete, the results indicate that RS-G-1.7 yields a less restrictive gross activity concentration (0.14 Bq/g or 3.8 pCi/g), while NUREG-1640 is more permissive for metals (0.34 Bq/g or 9.1 pCi/g). In either case, the differences are less than about a factor of two, which is in very close agreement, especially at these low dose levels. This example illustrates that the differences identified earlier on a radionuclide-by-radionuclide basis are expected to be even less pronounced in implementation or actual practice.

Regarding the possibility of imports, it is estimated that should the IAEA's RS-G-1.7 become an international standard, resulting industry practices might result in annual doses also on the order of 10 µSv, other things being equal. It should be noted that the types and amounts of materials that may be imported is uncertain, but they primarily consist of equipment, parts, and tools used by the nuclear industry. For example, companies involved in servicing power reactors and fuel fabrication facilities ship materials between service centers and power reactors or fabrication plants. As a result, the shipments involve the transfer of materials only between industrial facilities, and exposures to members of the public are very unlikely given that there is no subsequent applications of such materials within the public sector. Moreover, it is not realistic to expect that the nuclear industry would import materials and equipment specifically for disposal in U.S. landfills as the costs of doing so would be prohibitive. Consequently, doses to the public are expected to be a very small fraction of the limit being considered by this rulemaking, i.e., 10 µSv (1 mrem) per year.

3.3 Reuse and Trash

Additional assessments of normalized doses are addressed as supplemental reports to NUREG-1640 (NRC 2005c,d). Specific analyses of the reuse of various kinds of equipment range from small tools (e.g., hand tools) to large industrial equipment with operators assumed to be exposed in an enclosed environment, e.g., in the cab of a truck. Regarding trash, the amounts expected to be shipped for disposal in landfills is expected to be a very small fraction of that estimated for ferrous metals and concrete. Considering the practices of the nuclear industry, it is not realistic to expect that U.S. or European licensees would ship trash and other non-salvageable materials across international borders just for disposal. This is deemed impractical because of costs and regulatory constraints. Because of the reuse of tools and equipment or release of trash for disposal in landfills results in little or no residual radioactivity originating from licensed nuclear facilities, these scenarios are not included in comparisons with international guidance.

E-II SOURCES AND TYPICAL ANNUAL DOSES FROM BACKGROUND RADIATION

1. INTRODUCTION

Background is comprised of various sources of ionizing radiation. These sources collectively produce an average total effective dose equivalent of about 3 mSv/yr (300 mrem/yr) to a U.S. resident. For comparison, the estimate of the average U.S. radiological dose from background is similar to the world average estimate of 2.4 mSv/yr (240 mrem/yr). NUREG-1501 (NRC 1994a) contains a detailed discussion of sources, levels, and variability of background; the following discussion summarizes Section 2 of NUREG-1501. Additional information can be found in two reports issued by the National Council on Radiation Protection and Measurements (NCRP 1987a, b).

2. SOURCES OF EXTERNAL RADIATION

Radiological doses from background typically range between 1 mSv/yr (100 mrem/yr) and 10 mSv/yr (1,000 mrem/yr) in the United States. Although greater radiological doses are possible for people living in houses with very high radon concentrations, 10 mSv/yr could be taken as a practical maximum, with a few rare exceptions. Table E-1 provides a breakdown of the sources of natural background. In addition to the amounts in Table E-1, relatively minor contributors to the dose from background (less than 1 percent each) are cosmogenic radionuclides, created by the interaction of cosmic rays with otherwise stable elements present on earth, and man-made fallout radionuclides from nuclear weapons testing. Cosmogenic radionuclides include H-3, C-14, Ar-41, etc. (NCRP 1987a). Radionuclides from weapons fallout include H-3, C-14, Sr-90, Cs-137, Pu-239, etc. (NCRP 1987a).

Table E-1 Comparison of the Principal Components of Background Between Estimated Populations of the United States and the World

	Annual Effective Dose Equivalent (mSv)		
Component	**U.S. Mean[1]**	**World Mean[2]**	**World Range[2]**
Cosmic	0.27	0.36	0.3 – 2.0
Indoor radon and progeny	2.0	1.1	0.3 – 5.0
Internal (other inhaled, ingested)	0.4	0.5	0.2 – 1.0
Terrestrial gamma	0.28	0.41	0.2 – 1.0
Totals (rounded)	**3.0**	**2.4**	**1.5 – 6.0**

1. NCRP 1987a.
2. UNSCEAR 1988.
1 mSv = 100 mrem

Background produces radiological doses to the U.S. population that are highly variable between locations (spatial) and also over time at the same place (temporal). For example, cosmic radiation is modulated by the 11-year solar cycle and typically varies about 10 percent at the same location, but at different times. Temporal variability of background is also tied to atmospheric circulation and precipitation patterns that affect the distribution of cosmogenic and fallout radionuclides. Short-term changes in external gamma exposure arise from redistribution of radon decay products in the atmosphere and washout with precipitation, resulting in changes ranging from a few percent to more than 200 percent over the course of a day or season. Even larger variations in indoor radon concentrations can occur because of differential air pressures in buildings and resulting changes in ventilation rates. Indoor levels of gamma radiation typically vary by about 50 percent due to the use of different construction materials. Outdoors, changes in soil moisture and snow cover cause external gamma radiation levels to vary seasonally by 10 to 50 percent at the same location. The concentration of radionuclides that produce internal doses, such as Pb-210 in body tissues, has been observed to vary by about a factor of three throughout the United States. Spatial variability of cosmic radiation is observed to be as much as 200 percent, depending greatly on altitude and to a lesser extent on latitude.

3. SOURCES OF NATURAL RADIOACTIVITY IN MATERIALS

Nearly all materials contain naturally occurring radioactivity due to the presence of terrestrial radionuclides, such as K-40, Rb-87, Th-232, and U-238, and cosmogenic radionuclides, such as C-14, H-3, Be-7, and Na-22. The concentration of these radionuclides in soil, water, air, and living matter can vary widely throughout the country because of geological processes, climatic changes, weather, and human activities. For example, concentrations of uranium and thorium in the soil range from as little as one-tenth to as much as four times the average value. Data contained in Table E-2 illustrate a typical range of natural radionuclide concentrations in soil throughout the United States and the world.

Table E-2 Typical Ranges in Average Concentration of Background Radionuclides (Bq per kg)

Material	Uranium-238	Thorium-232	Potassium-40	Reference
Bauxite ore	250	200	n/a	UNSCEAR 1988
Coal, U.S.	18 (1–540)	21 (2–320)	52 (1–710)	Beck et al 1980a,b
Copper ore	30–80	23–110	n/a	UNSCEAR 1988
Crustal rock, U.S.	36	44	850	NCRP 1987a
Oil shale	56 (37–74)	24 (19–37)	481 (185–962)	Gogolak 1982
Phosphate fertilizer, U.S.	9200	n/a	n/a	UNSCEAR 1988
Soil, worldwide	25 (10–50)	25 (7–50)	370 (100–700)	UNSCEAR 1988
Soil, U.S.	37 (4–141)	36 (4–126)	n/a	Myrick 1983

1 Bq = 27.027 pCi

The concentration of the principal gamma-emitting radionuclides in soil is directly related to the external gamma radiation levels in a locale. On a nationwide scale, the concentrations of terrestrial radionuclides vary widely, which is reflected in the grouping of external gamma radiation levels into three regions:

- The Atlantic and Gulf coastal plains, which average about half of the level seen for Middle America (0.23 mGy/yr or 23 mrad/yr);

- Middle America, which has an average level of 0.46 mGy/yr (46 mrad/yr); and

- The Denver, Colorado area, which has an average level about twice that of Middle America (0.9 mGy/yr or 90 mrad/yr).

Throughout the United States, concentrations of naturally occurring radionuclides in ground water can also vary widely. In certain areas of the midwest, for example, the concentration of uranium in water (13 mBq/l or 0.35 pCi/l) is 35 times greater than that found in some eastern States (0.37 mBq/l or 0.01 pCi/l), but even greater concentrations are reported in western areas of the country, where natural uranium concentrations in ground water (130 mBq/l or 3.5 pCi/l) are 350 times that of eastern ground water.

On a smaller scale, such as within an individual State, background radioactivity levels can vary even more. For example, in a particular location in northwestern New Jersey, external gamma radiation levels triple across a small field and, at a nearby rock outcropping, the average soil concentration of naturally occurring radionuclides increases one-hundred-fold, yet 99 km (62 miles) away from this location, gamma radiation levels fall to less than 10 percent of the regional average due to the presence of sandy beaches.

4. MAN-MADE SOURCES OF RADIOACTIVITY

Spatial variability in the concentration of background radionuclides can also be caused by human activities. Fallout from a nuclear weapon test can change background abruptly and require a few months to a few decades to decay. Such testing has correspondingly increased the spatial variability of background because the distribution of fallout radionuclides in the United States is not homogeneous. The deposition of weapons fallout is dependent on meteorological conditions. Mining and milling have also increased the spatial variability of background by redistributing the preexisting concentrations of naturally occurring radionuclides in a locale. Another human activity that affects the spatial distribution of background is the combustion of fossil fuels which produces ash that redistributes natural radioactivity from the ground to the air.

In addition to naturally occurring sources of radiation, nuclear technology has led to the creation of man-made radionuclides that contribute to the background radiological dose. Man-made sources of ionizing radiation exposure account for 18 percent of the total radiological dose to the U.S. population. Of the man-made sources, medical x-ray examinations are the largest source of exposure, producing 11 percent of the total dose (0.39 mSv/yr or 39 mrem/yr). Nuclear medicine procedures account for 4 percent of the total population dose, followed by consumer products (3 percent), weapons test fallout (less than 1 percent) and occupational exposures (less than 1 percent). On average, however, 82 percent of the total dose to the U.S. population comes from naturally occurring radiation sources. The magnitude and variability of radiation doses is directly proportional to the background level that individuals are exposed to and the activities in which they are engaged. Because of their widely varying and ubiquitous characteristics, radiation doses to U.S. residents from background, in turn, vary widely, as well.

E-III POPULATION COLLECTIVE DOSE DUE TO BACKGROUND RADIATION

As was noted earlier, individual doses from background radiation typically range between 1 mSv/yr (100 mrem/yr) and 10 mSv/yr (1,000 mrem/yr) in the United States. It is sometime necessary to assess radiation exposures to an entire population, as compared to just one individual member (NCRP 1995). In simple terms, the collective dose of a population is the sum of the dose received by each individual within that population group. An important distinction in the concept of collective dose is that it addresses members of population groups and not members of the critical group as is defined in the context of regulatory dose limits. Collective dose is derived as:

$$S = \Sigma H_i P_i$$

where:

S = collective to the population
H_i = dose to each individual in group i
P_i = population group i

Collective dose is expressed in person-rem or person-sievert. For example, lets assume that the annual doses to members of two groups of individuals are 0.8 and 1.2 mSv each, with a population of 1,250 and 800 persons in each group, respectively. For this example, the collective dose of each group is estimated as:

0.8 mSv x 1,250 persons = 1,000 person-mSv
1.2 mSv x 800 persons = 960 person-mSv

The results indicate that although doses and population sizes are different, the resulting collective doses are essentially identical. This example also illustrates the competing effects of individual doses and sizes of populations on the collective dose. In this example, the differences in doses and sizes of the populations nearly cancel one another out.

It can be seen that collective dose may be a useful index in differentiating dose impacts when population sizes and doses vary. However, a number of inherent limitations have been identified in the application of collective dose (NCRP 1995). Of specific interest, is whether there is a justification for excluding negligible individual doses from collective dose calculations. The NCRP notes that all doses should be included in assessing collective doses and “there is no conceptual basis for excluding any individual doses, however small.” However, the NCRP recognizes that there may be legitimate practical limitations for doing so. Another issue addresses itself to uncertainties in the types of exposed populations, size of the exposed populations, and exposure pathways, among others. Regarding uncertainties in the underlying components on which collective doses are based, the NCRP states that collective doses should not be used when the uncertainty in the number of individuals summed in the population component of the dose is large, i.e., greater than one order of magnitude. Similar care should be considered in evaluating the other components used in calculating collective doses. Finally, there may be a justification in identifying a collective dose threshold below which it should be recognized that there may be no significant impacts, nor risks. The NCRP recommends a threshold based on 10 percent of the reciprocal of the risk coefficient. Using the NCRP approach, the collective dose threshold for a risk coefficient of 4×10^{-2} per Sv (4×10^{-4} per rem) would be 2.5 person-sievert (250 person-rem), used here only as an illustrative example. Chapter 3 of the GEIS addresses collective doses in the context of the alternatives.

The collective dose to the U.S. population associated with background radiation has been estimated using typical sources of radioactivity and resulting radiation doses. The annual collective dose from background radiation in the United States is estimated to be about 840,000 person-Sv (84 million person-rem), assuming an annual average effective dose equivalent of 3 mSv (300 mrem) and a population of about 280 million (NCRP 1987b, 1995).

E-IV EXPOSURES FROM MULTIPLE SOURCES DERIVED FROM THE RELEASE OF MATERIALS FROM LICENSEES

1. INTRODUCTION

Assessment of the potential doses to an individual that could arise from the release of materials from a licensed facility were performed according to particular activities, called scenarios. The scenarios involved the transport, processing, refining, consumer use, and disposal of these materials. Conceptually, multiple scenarios could apply to the same individual, and this potential raises the question of what would be the exposure and the probability of such an occurrence. That is, what would be the consequence and the frequency of multiple scenarios affecting the same individual–the risk. The possibility of multiple scenarios concurrently applying to an individual implies that the individual would be exposed to very low levels of radioactivity from more than one source, for example from a vehicle's engine block and recycled concrete in a roadbed. The range of potential doses from multiple exposures, should they occur, and the potential for their occurrence are assessed below.

Many exposure scenarios were assessed for each radionuclide and each material to evaluate those circumstances that could lead to the greatest exposures following the release of materials [see NUREG-1640 (NRC 2003d)]. These scenarios are the critical group scenarios for that material. The scenario that yielded the greatest exposure to an individual in a year, regardless of the material, was identified for each radionuclide on a per unit of radioactivity basis. This scenario is not only the critical group scenario for that material and radionuclide, but also the overall critical group scenario for that radionuclide. For example, road building with recycled concrete is the scenario that potentially gives the greatest exposure for Co-60 for each Bq per gram. Other scenarios involving the processing, refining, consumer use, and disposal of iron, steel, copper, and aluminum gave less potential exposure from Co-60 for each Bq/g.

2. MULTIPLE POTENTIAL EXPOSURES

Several hypothetical situations could arise where an individual could be exposed from the release of several different types of materials, products made from them, disposals in landfills, or reuse of equipment once released. There could be multiple radionuclides involved, or multiple kinds of materials released, or multiple concurrent scenarios. Such scenarios might include multiple facilities releasing materials, processing released materials while using consumer products made from released materials, reuse of tools and equipment, or disposal of materials from multiple licensees in one landfill. The potential exposures from these hypothetical situations are examined below.

2.1 Multiple Radionuclides and the Sum of the Fractions Rule

The standard regulatory approach for implementing limits involving multiple radionuclides requires that the sum of the fractional concentrations, the nuclide concentration divided by the concentration limit for each respective nuclide, be kept less than one. This is often known as the "sum-of-the-ratios rule," and is described in footnote 4 to App. B of 10 CFR Part 20. Use of this rule limits the contribution to the overall exposure of an individual from any one radionuclide to a fraction of the overall allowed level when more than one radionuclide is present.

2.2 Multiple Materials - Implementation Based on the Overall Critical Group Scenario for Each Radionuclide

Implementation of a regulation for the release of solid materials would likely be dose-based. Thus, to ensure that individuals would be protected regardless of the material being released, the release criteria of a particular radionuclide, for example, Co-60, would be based on the most restrictive scenario for that radionuclide and critical group scenario. Then, that concentration would be applied to all materials. In this case, the same concentration that could give a certain dose, say 10 μSv (1 mrem) in a year, for road building with recycled concrete, would also be applied to the release of iron, steel, copper, and aluminum with associated Co-60. That concentration would give less than 10 μSv in a year for any of these other materials, even in the most restrictive scenario for other materials. For every other scenario, the potential dose actually would be less than 10 μSv in a year because the release criteria would be a lower concentration than could result in 10 μSv in a year. The effects of these small doses are bounded and addressed in the following discussions. The most restrictive scenarios of all materials do not include any scenario from the assessments of copper or aluminum, because their contributions are much smaller when compared to the most restrictive ones listed in Table E-3. For materials with radionuclides only on the surface (surface concentrations as compared to the previous discussion on volume concentrations), the overall critical group scenarios are limited to steel and copper. Concrete scenarios disappear from this latter list due to the mixing of the surficial radionuclides in rubble. That is, there is usually a greater relative thickness of concrete - mass to surface ratios - in buildings and structures.

Table E-3 Overall Critical Group Scenarios Bq/g Basis

Iron & Steel	
	SCENARIO
	Processing steel at scrap yard
	Leachate from steel slag
	Handling slag at steel mill
	Processing steel slag for road construction
	Emission of airborne effluents from furnace
Concrete	
	SCENARIO
	Processing concrete
	Road building
	Leachate–industrial
	Leachate–Municipal solid waste
	Truck driver

2.3 Multiple Concurrent Scenarios

Hypothetically, it is possible that an individual could be exposed through multiple concurrent scenarios. A hypothetical example is given to illustrate this possibility. The approach that is used to illustrate this hypothetical example is to add a number of scenarios to maximize the potential dose to an individual. For reasons described later, the likelihood of such multiple concurrent exposures becomes vanishingly small as the number of potential concurrent scenarios increases.

Some combinations of scenarios can be ruled out, because they are impossible or very highly unlikely. For example, it is impossible to be in two places at once, there are only twenty-four hours a day, some scenarios take place in different years after release, and there is a very low percentage of the population who are fully employed concurrently in two or more jobs covered by these scenarios. For example, it is reasonable to assume that it is very highly unlikely that the same individual would be employed at the same time during an entire year as full-time road builder using processed concrete and also as a full-time slag handler at a copper refinery where both facilities are processing released materials during that year.

However, other combinations of scenarios are possible and these merit analysis. From Table E-3, a hypothetical set of concurrent scenarios that are also credible can be assembled with only two scenarios. A full-time job and residing downwind from a refinery could occur concurrently. Hypothetically, the expected exposure (from two scenarios) could be up to 20 μSv (2 mrem) in a year, if the limit for release were based on 10 μSv (1 mrem) in a year. More credible conjunction of concurrent scenarios can be hypothesized if the less-than-overall-critical group scenarios are added. However, the hypothetical exposures from each of the other scenarios would be expected to add less than the dose upon which release would be based, e.g., less than 10 μSv in a year.

A hypothetical road builder using processed concrete material with associated cobalt-60 could drive to work over a roadbed made from aggregate with associated thorium-232. He could live within the area that is in the effluent pathway of a refining furnace. Furthermore, he could drive a truck with an aluminum engine block, and use aluminum cookware and jewelry made from recycled metals. Hypothetically, if a release regulation were to limit the mean individual dose to the critical group to, for the purposes of clarity and illustration, 10 μSv in a year from release, and if the implementation of the regulation takes into account the practices described above, as shown in Table E-4, the dose to the hypothetical individual, calculated from the results in NUREG-1640 (NRC 2003d), would be approximately 30 μSv (3 mrem) in a year or three percent of the public dose limit, which is 1,000 μSv (100 mrem) in a year (see Subpart D to 10 CFR Part 20).

As shown in Table E-4, even when, for illustrative purposes, an extremely conservative and highly implausible situation is considered for estimating individual dose, where six hypothetical exposures occur concurrently, the resulting dose is only 30 μSv in a year. The underlying assumption for making the above dose estimate assumed that several different licensed facilities that use different radionuclides come together to make this situation possible and all these

Table E-4. Hypothetical Multiple Concurrent Scenarios

Scenario	Nuclide	Material	Dose[1] (μSv in a year)
Road builder	Cobalt-60	Concrete	10
Driving on road	Thorium-232	Concrete	10
Air borne emissions	Iodine-125	Steel	10
Aluminum engine block	Cobalt-60	Aluminum	0.009
Aluminum cookware	Protactinium-231	Aluminum	0.008
Copper object on body	Silver-108m	Copper	0
			Total 30.017

[1]NUREG-1640, mass based mean effective dose.

facilities released materials at the maximum release concentration levels. A more realistic estimate of the dose to this hypothetical individual would be significantly less than 10 μSv in a year from each of the six scenarios, and a more realistic cumulative total dose would be less than 30 μSv in a year. This is much more than adequate protection of the public because, for adequate protection of the public, NRC requires that each licensee conduct operations so that the total effective dose equivalent to individual members of the public from the licensed operation does not exceed 1,000 μSv in a year.

2.4 Potential for Occurrence of Multiple Concurrent Scenarios

The potential for the same individual to be involved in concurrent scenarios is physically constrained by the relatively limited amount of materials that could be released from licensed facilities. Geographical distances between licensees and the different locations where the scenarios could occur also decrease the potential for concurrent scenarios to affect a single individual. From the above lists of scenarios that could result in the highest doses, it can be seen that many involve specialized industrial processing. There are not many of these processors in the country, and thus, only a limited number of individuals could be affected by those scenarios. Such individuals would likely be affected by only one processing scenario. The more likely scenarios that could affect these processors would involve consumer products or use of public roads. The potential that a particular consumer product made from released materials is used by the same hypothetical individual depends on the number of such products made, the total number of these products made from released materials and the fraction of those made that are in use.

The potential for a processor to be affected by additional scenarios is the serial multiplication of each additional scenario. While it is difficult to estimate the actual probability of a particular scenario[1], an example can illustrate that with each additional scenario, the potential for all the

[1] Data are usually not available to calculate the probability, however, an example of an approach to make such an estimate illustrates that the probabilities of these scenarios is usually small. Consider the probability of an auto with a cast-iron engine block containing radionuclides that were released in steel. From NUREG-1640, the fraction of iron castings that are used for the auto and truck industry is 0.5. The

(continued...)

scenarios occurring together becomes smaller. Even with only a few scenarios, this potential is very small. For example, in the illustrative case above, six scenarios were hypothetically aggregated. A relatively large estimate of the likelihood that any of the additional scenarios would affect the hypothetical road builder above would be one-in-a-hundred, or 0.01. If only one additional scenario affected the hypothetical road builder, then there would be an estimated one-in-a-hundred chance that this individual would be exposed to as much as 20 µSv in a year. The potential for two additional scenarios would be estimated as 0.01 x 0.01 = 0.0001 or one-in-ten-thousand in a year to be exposed to something less than 30 µSv in a year. Repeating this process for each additional scenario in our hypothetical example above gives an estimate of one-in-ten-thousand million that this hypothetical individual would be exposed to less than 30 µSv in a year. Considering that the population of the U.S. is approximately 280 million, this is a very small potential as the probability indicates that no one individual in the entire U.S. is likely to be affected by six concurrent scenarios.

2.5 Landfill Disposal

Materials released from licensed facilities may be disposed of in regulated landfills. The types of disposal facilities include municipal solid waste (MSW) landfills, industrial landfills (IL), and construction and demolition (C&D) landfills. Collectively, these facilities are referred to as Subtitle D landfills under EPA regulations. Municipal solid waste landfills are regulated under 40 CFR Part 258, and industrial landfills and construction and demolition landfills are regulated under 40 CFR Part 257. In addition, State and local agencies regulate landfill siting, design and construction, operation, surface and ground water monitoring and corrective action, closure and post-closure care, and financial assurance. Municipal solid waste landfills are required to install a cap upon closing each disposal cell, and a composite bottom liner and a leachate collection system. Performance standards include requirements to limit the amounts of leachate accumulations at the bottom of disposal cells, specifications on leachate release rates out of landfills, and chemical concentration limits in ground water. Industrial landfills are not required to have bottom liners and leachate collection systems. However, all landfills are required to operate in a manner that will not cause discharges of pollutants into surface water or ground water in violation of the requirements of the Clean Water Act and Safe Drinking Water Act.

Such requirements are expected to mitigate exposures and doses to both landfill workers and nearby members of the public. For example, MSW landfills are required to place a daily soil cover over wastes. The presence of a soil cover is expected to reduce worker exposures from external radiation, dust inhalation, and incidental ingestion of materials. The cover is also

[1] (...continued)
fraction of all scrap that is used for casting is 0.2. If all the scrap that could potentially be released from the nuclear industry were to be used in one year, it would be one-thousandth of all the scrap used that year. Thus, the fractional mass of released metal in new engine blocks would be one-ten-thousandth. This fraction can be used as an estimate of the probability of getting a new engine block with released metal. That probability is then multiplied by the probability that the hypothetical individual is driving a new auto. Therefore, an estimate for the probability of a single scenario occurring of one-in-one-hundred is likely an overestimate, but it is useful to illustrate a conservative upper bound of the probability.

expected to reduce fugitive dust emissions and airborne materials at downwind locations, thereby reducing inhalation exposures to nearby residents. The control of leachate discharges, landfill closure, and the post-closure care and monitoring periods are part of the process required to mitigate impacts on surface and ground water. These requirements are designed to minimize discharges from closed disposal cells and reduce or eliminate impacts on nearby usable surface and ground water resources.

In considering the disposal of materials from multiple licensees, although possible, the dumping of released materials is expected to be governed by several factors. First, the disposal of materials is driven by the availability of nearby landfills, disposal capacity of each landfill, and restrictions placed by each landfill on the types of wastes it may accept. As a result, it is expected that in some cases, disposals will be shared by two or more landfills, and in other instances, disposals may be confined to a regional, and possibly larger, landfill. Second, the sequence in which shipments of released materials are sent for burial can be considered as independent events, with shipments occurring on a schedule driven by the need of each licensee. The likelihood that two licensees might ship materials at the same time and arrive at the landfill for disposal also at the same time is very unlikely. Third, the disposal process at landfills is often organized by disposal cells, where burials are segregated by types of wastes and volumes. In such instances, materials sent by two licensees would most likely be dumped in separate disposal cells, and processed by different work crews. Together, these factors are anticipated to minimize exposures to both workers and members of the public.

In light of regulatory requirements imposed on the operation and closure of landfills, and post-closure monitoring, doses to both landfill workers and nearby residents are expected to be well below the release limit. Other factors that are expected to contribute to still lower doses include the remote possibility of multiple disposals occurring at every single landfill, the segregation of materials by disposal cells, and disposal activities being conducted by different work crews. Finally, the application of the most limiting unrestricted release scenario and its corresponding radionuclide concentrations as release criteria would tend to result in doses that are less than 10 uSv (1 mrem) per year, even when considering multiple disposal events at a single landfill.

2.6 Equipment Reuse

The type of equipment that could be released from nuclear facilities for reuse in an environment free of radiological controls ranges from small items, such as hand tools, to very large ones, such as mechanized equipment and industrial vehicles. The release of equipment is a dynamic process involving different types of facilities and activities, such as routine operations, research and development, and plant outages, refurbishment, and decommissioning. In addition, this process is taking place simultaneously at thousands of facilities across the nation and being conducted every day. As a result, it is not readily possible to define what types of items and how many are routinely used in radiologically controlled areas, what fraction is surveyed and released for reuse versus those that are discarded as low-level radioactive waste, and assign representative residual radioactivity levels by radionuclides and relative mix for all licensees.

Doses to workers using tools and equipment that have been released depend on several factors. For example, the dose is directly proportional to the number of hours that a worker is assumed to handle reused items. Time spent on other activities that do not require the use of any equipment that was released would result in lower doses. Another consideration is whether other equipment and tools may be available that are not a product of release, i.e., equipment of other origins that were never introduced in radiologically controlled areas. For equipment that have been released, the duration of exposure to workers is confined to its useful life-cycle. The useful life of equipment is driven by operational conditions and economic considerations, taking into account replacement and repair costs. These factors are expected to be different among facilities. For large equipment (e.g., trucks), the useful life is typically much longer than that of small equipment, such as hand tools. The useful life of small equipment is much shorter as these items are discarded given that replacement costs are usually less than repair costs. Also, the dose is directly proportional to the total number of items being used by a worker at any one time. For large equipment, such as mechanized equipment, a worker can only operate one piece of equipment at a time. However, for small equipment, such as hand tools, it is conceivable that a worker could use a number of items or at least be surrounded by several such small tools while working. Other mitigative measures are associated with different practices among licensees, such as whether equipment and tools are protected (by wrapping in plastic) before being introduced in controlled areas; the types of administrative controls used for releasing equipment; conditions on the types of equipment that may be released *versus* those that are discarded as radioactive waste; and the application of constraints on how equipment may be used after having being released.

In practice, licensees control equipment and tools that are introduced in radiologically controlled areas. In some instances, licensees supply all equipment and tools for use in controlled areas, thereby minimizing the constant flux of equipment being processed in and out of such areas. Also, equipment and tools are surveyed before being taken out of radiologically controlled areas. Such surveys consist of conducting scans with a radiation survey meter and taking wipes to assess the presence of removable surface activity. The presence of radioactivity on wipes is evaluated using separate instrumentation. Some survey methods involve the introduction of the item into an instrument that measures radioactivity from all external and internal surfaces. Depending on the results of the survey, the items are either cleaned to meet release criteria, not taken out of the controlled area and set aside for later use in the same work area, or simply discarded as low-level radioactive waste. Moreover, experience has shown that cleaning efforts involve a process in which residual radioactivity levels are removed to non-detectable levels, as opposed to cleaning to a level that just meets release criteria. In recognition of operational practices and application of ALARA by licensees, it is expected that the presence of residual radioactivity on released equipment would be well below release criteria and should result in doses that are less than 10 uSv (1 mrem) per year, even when considering the use of multiple small items.

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