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Derivation of Accident-Specific Material-at-Risk Equivalency Factors

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1. Introduction

A method for calculating plutonium equivalent grams (PEG) is derived from the cumulative effective dose (CED) equation. This methodology allows application of facility specific accident and material types in order to determine PEG factors which can be used in comparing the dose consequences of various different nuclide spectrums. In conjunction with near real time material tracking, the PEG methodology can add considerable process flexibility while creating a simple metric to ensure that the bounds of analysis are not exceeded.

2. Methodology

2.1 Background of Dose Calculations

PEG is an evaluation methodology which allows direct comparison of the inhalation pathway dose consequences of different material-at-risk (MAR) nuclide distributions. This objective is achieved by deriving a comparison between the number of grams of a reference nuclide that has equivalent dose consequences as a given MAR. This approach has been labeled PEG because the chosen nuclide of reference is Pu-239, primarily because it is a nuclide of particular interest. The International Commission on Radiological Protection (ICRP) issues dose conversion factors for workers in ICRP 68, "Dose Coefficients for Intakes of Radionuclides by Workers,"[1] and for the public in ICRP 72, "Age Dependent Doses to the Members of the Public from Intake of Radionuclides Part 5, Compilation of Ingestion and Inhalation Coefficients."[2] Using these dose conversion factors and accounting for dry deposition of the material during transport, the CED can be calculated as:

$$CED = \frac{\chi}{Q} \cdot BR \cdot \sum_{i=1}^{N} \{ST_i \cdot DDF_i \cdot DCF_i\} \quad (1)$$

where:

$\frac{\chi}{Q}$	=	Plume dispersion (s/m^3)
BR	=	Breathing rate (m^3/s)
ST_i	=	Source term of nuclide *i* (Bq)
DCF_i	=	Dose conversion factor of nuclide *i* (Sv/Bq)
DDF_i	=	Fraction of nuclide *i* remaining in plume after dry deposition (no units)
N	=	Number of nuclides contributing to dose (no units)

The χ/Q plume dispersion value is a function of the meteorological conditions involved in the accident and relative location of the release point and the receptor. Generally, χ/Q is considered to be constant for all nuclides of respirable size in an event and is independent of particular nuclide and source types. BR is a property of the receptor and is subsequently independent of all nuclides and sources involved in an accident.

The DCF accounts for the actual radiation dose to the receptor per unit of material uptake, and is listed in ICRP 68 for workers and ICRP 72 for the public. For inhalation dose calculations, this factor is dependent upon particle size as well as the chemical state of the nuclide, **both of which are functions of material type and accident scenario**. Selection of particle sizes should be

determined according to the ICRP recommendations, unless accident conditions render a different selection more justifiable. Section 2.1 of ICRP 68 recommends a five micron particle size as more representative of workplace aerosols. This PEG definition also provides the flexibility to use a more appropriate lung clearance type for the dose conversion factor than simply assuming the most conservative factor when nuclide properties are well characterized. In cases where these properties are unknown, the most conservative DCF applicable should be used.

The dry deposition factor (DDF) accounts for the material that is removed from the plume via deposition on the ground and accounts only for plume depletion that is expected to occur, independent of weather conditions.

The source term can be calculated using the source term equation:

$$ST = MAR \cdot SA \cdot DR \cdot ARF \cdot RF \cdot LPF \qquad (2)$$

Where:

ST	=	Source term (Bq)
MAR	=	Material-at-risk (g)
SA	=	Specific activity (Bq/g)
DR	=	Damage ratio (no units)
ARF	=	Airborne release fraction (no units)
RF	=	Respirable fraction(no units)
LPF	=	Leak path factor (no units)

In the source term equation, the DR, ARF, RF and LPF are all dependent upon the physical and chemical form of the MAR as well as the specific accident analyzed. Subsequently, a fully characterized source term is derived with an understanding of the appropriate physical and chemical phenomena in the accident progression and contains the quantity, the physical characteristics, and the chemical form of the material released to the environment.

In calculating the dose consequences to a receptor as the result of an accident, two major stages exist. The first stage is the progression of the accident that causes some radiological MAR to be released. This process is represented by the source term equation (equation 2). The second major stage involves the transport of this released source term through the environment to a receptor who will inhale the material. The airborne transport process and subsequent uptake is represented by the CED equation (equation 1).

2.2 Derivation of Plutonium Equivalent Grams Technique

PEG can be used to provide equivalent values to compare materials having different nuclide distributions. To make such a comparison one must determine how many grams of a particular reference plutonium nuclide would result in a dose that is equivalent to each material composition and quantity. PEG, in grams, can be determined using equations 1 and 2 as expressions of the CED from a given material.

$$CED = \frac{\chi}{Q} \cdot BR \cdot PEG \cdot SA_{Ref} \cdot DR_{Ref} \cdot ARF_{Ref} \cdot RF_{Ref} \cdot LPF_{Ref} \cdot DDF_{Ref} \cdot DCF_{Ref}$$
$$= \frac{\chi}{Q} \cdot BR \cdot \sum_{i=1}^{I} \{MAR_i \cdot SA_i \cdot DR_i \cdot ARF_i \cdot RF_i \cdot LPF_i \cdot DDF_i \cdot DCF_i\} \qquad (3)$$

The subscript *Ref* indicates the selection of a reference isotope and accident scenario, while *i* represents the individual nuclides in a spectrum, with *I* being the total number of nuclides. This

comparison is performed for the same facility and receptor; therefore, the plume dispersion and breathing rate factors on both sides cancel each other out and the resulting equation is:

$$PEG \cdot SA_{Ref} \cdot DR_{Ref} \cdot ARF_{Ref} \cdot RF_{Ref} \cdot LPF_{Ref} \cdot DDF_{Ref} \cdot DCF_{Ref} = \sum_{i=1}^{I} \{MAR_i \cdot SA_i \cdot DR_i \cdot ARF_i \cdot RF_i \cdot LPF_i \cdot DDF_i \cdot DCF_i\} \quad (4)$$

In order to determine the equivalent MAR of the reference material, all other factors can be placed on one side of the equation, and the PEG value can be isolated:

$$PEG = \sum_{i=1}^{I} MAR_i \cdot \left\{\frac{ASF_i}{ASF_{Ref}}\right\} \cdot WF_i \quad (5)$$

Where:

$$ASF_i = SA_i \cdot DR_i \cdot ARF_i \cdot RF_i \cdot LPF_i \cdot DDF_i \quad (6)$$

and

$$WF_i = \frac{DCF_i}{DCF_{Ref}} \quad (7)$$

The PEG represents the mass of the reference nuclide which would result in a dose equivalent to the identified MAR nuclide spectrum and is measured in grams. The activity scaling factor (ASF) represents the scaling of the material from grams to units of activity. It also accounts for the amount of a nuclide that is actually damaged, released, and respirable based upon a specific accident type and includes the plume depletion via dry deposition. The ASF has units of (Bq/g). The definition of ASF in equation 6 is also valid for the reference material. The weighting factor (WF) represents the relative dose consequences to a receptor of particular nuclide and chemical form *i* with respect to an equivalent inhaled activity of the reference nuclide and chemical form and has no units. A PEG factor (EF_i) for converting a MAR_i of a particular nuclide to an equivalent MAR of the reference nuclide, PEG, can be defined by combining the accident dependent ASF values and the chemical form dependent WF values.

$$EF_i = \frac{ASF_i}{ASF_{Ref}} WF_i \quad (8)$$

$$PEG = \sum_{i=1}^{K} \{MAR_i \cdot EF_i\} \quad (9)$$

Once the conversion of various nuclide compositions and or streams to PEG has occurred, then the generated equivalent PEG can be used in calculating the CED for the given nuclide composition.

$$CED = \frac{\chi}{Q} \cdot BR \cdot PEG \cdot SA_{Ref} \cdot DR_{Ref} \cdot ARF_{Ref} \cdot RF_{Ref} \cdot LPF_{Ref} \cdot DDF_{Ref} \cdot DCF_{Ref} \quad (10)$$

3. Example Problem

In order to demonstrate how this PEG concept can be applied, consider the processing of an imaginary pseudo fuel, which may be subject to both a drop/crush event as well as a fire event. This imaginary fuel sample consists of five isotopes, Am-241, Pu-239, Cs-137, Sr-90, and I-131. The accident-specific release parameters for each of these isotopes are listed below in Table 1.

Table 1. Accident Specific Parameters for Psudeo Fuel Accidents

Event	Elements	DR	ARF	RF	LPF	DCF
Fire	All but Gasses	1.0	6.00E-03	1.00E-02	1.0	Oxide
	Fission Product Gasses	1.0	1.0	1.0	1.0	Largest
Drop	All but Gasses	1.0	2.30E-05		1.0	Largest
	Fission Product Gasses	1.0	1.0	1.0	1.0	Largest

Given these accident specific parameters, the isotope-specific ASF_i values can be calculated for each accident event. These ASF_i values can be seen below in Table 2. Note that for this example calculation, Pu-239 subject to the drop accident will be the reference isotope and event. Subsequently, to aid in identification, the Pu-239 drop components in the next two tables are bold italicized.

Table 2. Calculated ASF Values by Isotope and Accident

		Common to Both Accidents			*Drop Accident*	*Fire Accident*			*Calculated ASFs*	
Nuclide	SA	DR	LPF	DDF	ARF-Drop	RF-Drop	ARF-Fire	RF-Fire	ASF-Drop	ASF-Fire
Am-241	3.43E+00	1.0	1.0	1.0	2.30E-05	6.00E-03		1.00E-02	7.89E-05	2.06E-04
Pu-239	6.22E-02	1.0	1.0	1.0	2.30E-05	6.00E-03		1.00E-02	***1.43E-06***	3.73E-06
Cs-137	8.70E+01	1.0	1.0	1.0	2.30E-05	6.00E-03		1.00E-02	2.00E-03	5.22E-03
Sr-90	1.36E+02	1.0	1.0	1.0	2.30E-05	6.00E-03		1.00E-02	3.13E-03	8.16E-03
I-131	1.24E+05	1.0	1.0	1.0	1.0	1.0	1.0	1.00E-02	1.24E+05	1.24E+05

Using the appropriate worker dose conversion coefficients from ICRP 68, the isotope and accident specific weighting factors can be calculated and then combined with the ASF values calculated in Table 2 to determine the PEG equivalency factors as shown below in Table 3.

Table 3. Isotope and Accident Specific DCF, WF and EF Values for Psuedo Fuel

Nuclide	Drop DCF	Fire DCF	Drop WF	Fire WF	Drop EF	Fire EF
Am-241	2.70E-05	2.70E-05	8.44E-01	8.44E-01	4.65E+01	1.21E+02
Pu-239	3.20E-05	8.30E-06	***1.00E+00***	2.59E-01	***1.00E+00***	6.77E-01
Cs-137	6.70E-09	6.70E-09	2.09E-04	2.09E-04	2.93E-01	7.64E-01
Sr-90	3.00E-08	3.00E-08	9.38E-04	9.38E-04	2.05E+00	5.35E+00
I-131	1.10E-08	1.10E-08	3.44E-04	3.44E-04	2.98E+07	2.98E+07

Using the EF values derived in Table 4 and arbitrary masses for the particular nuclides in the pseudofuel allows for comparison of the effects of each individual accident as shown below in Table 4.

Table 4. Example PEG Calculations

Nuclide	Sample Mass (g)	Drop PEG	Fire PEG
Am-241	1	4.65E+01	1.21E+02
Pu-239	10	1.00E+01	6.77E+00
Cs-137	1	2.93E-01	7.64E-01
Sr-90	1	2.05E+00	5.35E+00
I-131	1.00E-06	2.98E+01	2.98E+01
Total	**13.00**	**8.87E+01**	**1.64E+02**

4. Conclusion

Using the derived PEG methodology and specific accident scenarios and material types, PEG equivalency factors can be derived for a specific facility or process. These factors can be used to compare the relative dose consequences of various nuclide spectrums under the conditions for which the factors were derived. The derived equivalency factors are specific to the material forms (physical and chemical composition) and accidents analyzed (i.e., fire involving fuel *and* oxide chemical state). The use of these factors for accidents, material types, receptors, or combinations of the three not analyzed in this derivation would be incorrect and possibly non-conservative.

5. References

1. ICRP 68, "Dose Coefficients for Intakes of Radionuclides by Workers," 1995.

2. ICRP 72, "Age Dependent Doses to the Members of the Public from Intake of Radionuclides Part 5, Compilation of Ingestion and Inhalation Coefficients," 1996.