THE DEVELOPMENT OF EQUIVALENCY FACTORS FOR RADIOACTIVE SUBSTANCES FOR USE IN THE LCA FRAMEWORK

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ABSTRACT

A fundamental requirement of an Environmental Management System (EMS) is to assess the significance of impacts in order to set priorities for improvement. The Environmental Aspect Register is the cornerstone of an EMS where contributions, material inventories and controls are summarised and it is this document that needs to be scrutinised and screened to identify significant impacts. Life Cycle Assessment (LCA) is an objective methodology that can be used to assess the environmental impact of a product, process or activity. This paper discusses the development of a methodology to allow the inclusion of radioactive discharges into the LCA framework. A number of specific parameters are identified which describe the fate and effect of radioactivity in the environment and these are used to derive a formula for calculating Equivalency Factors to allow a linear comparison of substances released into air and water.

INTRODUCTION

The first examples of environmental assessment of products were carried out on packaging and published at the end of the 1960s and the beginning of the 1970s in the US. They were called “Resource and Environmental Profile Analyses” (REPAs) and focused primarily on energy consumption, resource consumption and generation of waste, in accordance with the environmental debate at the time [1].

At the beginning of the 1980s, interest in the environmental assessment of products grew in connection with discussions on environmental impacts from various forms of packaging, and LCAs were used in several European countries to compare different beverage packaging.

From the end of the 1980s to today, interest in LCA has grown strongly, with a number of differing and increasingly complex products and systems being assessed.

Life Cycle Analysis Methodology

Life cycle analysis is a technique, which has gained acceptance as a means of quantifying environmental effects. The process is broken down into the following steps:

1. Goal definition and Scope
2. Inventory Analysis
3. Impact Assessment
4. Improvement Analysis

The impact assessment phase of LCA seeks to turn inventory data into impact information to support decision-making. The author has selected the following new impact categories for radioactive discharges:

- Environmental Irradiation to Air
- Environmental Irradiation to Water

Impact assessment is divided into four sub-sections:

1. Classification
2. Characterisation
3. Normalisation
4. Valuation

In classification the different releases are assigned to relevant impact categories. Characterisation is a quantitative step in which the relative contributions of each input and output to the assigned categories are assessed through the application of impact potentials or equivalency factors (EF). Usually a linear characterisation factor is found which expresses the potential contribution to a category per mass of an input or output in the inventory thus:

$$S_{ji} = M_i Q_{ji} \qquad \text{(Eq. 1)}$$

Where:

Sji potential contribution to impact j from input or output i

Mi Environmental quantity (mass of input or output i)

Qji characterisation factor (impact potential or equivalency factor) for substance i to impact category j

The total potential contribution to the impact category j from all inputs and outputs can then be calculated [2] as:

$$S_j = \sum_i S_{ji} \qquad \text{(Eq. 2)}$$

Normalisation is an optional step that employs factors to modify the results of the characterisation exercise to better understand the relative magnitude of the impact categories.

Valuation is another optional step within the impact assessment framework and is the process whereby different impact categories are weighted using numerical factors based on value choices.

This paper describes the development of EFs for a range of radioisotopes for use in the characterisation step of the LCA impact assessment process.

Development of Equivalency Factors for Radioactive Substances

There are at present no agreed quality standards for individual radionuclides in the environment. The approach proposed is designed to determine EFs for a range of radionuclides released into water and air. These EFs can be used to determine environmental impact that is compatible with the Life Cycle Impact assessment (LCIA) framework.

Establishing equivalency between various radioactive environmental interventions will allow for aggregation into common units for a meaningful comparison. An extensive review of literature describing the environmental behavior of the following radioisotopes has been carried out: Plutonium; Americium; Tritium; Cobalt; Caesium; and Uranium.

The following parameters were are identified that describe the fate and effect:

- *Parameter 1* *Life time in the environment based on half life (years)*
- *Parameter 2* *Total activity (Bq)*
- *Parameter 3* *Concentration per mass/specific activity (Bq/g)*
- *Parameter 4* *Energy (MeV)*
- *Parameter 5* *Linear Energy Transfer (LET)*

- *Parameter 6* *Radiation type alpha, beta or gamma*
- *Parameter 7* *Ozone creation potential (releases to air only)*
- *Parameter 8* *Bioaccumulation in soil and freshwater systems (non-living organisms)*
- *Parameter 9* *Bioaccumulation in biota (living organisms)*
- *Parameter 10* *Biological half-life in indicator species*
- *Parameter 11* *Residence time in soil/water*
- *Parameter 12* *Radio-sensitivity of indicator species*
- *Parameter 13* *Chemical behavior and toxicity of the radionuclide*
- *Parameter 14* *Chemical behavior and toxicity of the stable isotope(s) associated with the decay of the radioisotope*
- *Parameter 15* *Chemical form and reactions of the species intercepted*
- *Parameter 16* *Behavior once ingested or inhaled by species*
- *Parameter 17* *Chemical properties of receiving media (water/soil)*
- *Parameter 18* *Presence of other hazardous substances*
- *Parameter 19* *Solubility of radionuclide*

One of the most important aspects in quantifying radioactive discharges is to establish how persistent it is in the environment. Solberg-Johansen [2] proposed that the concentration of radionuclides in the environment is related to the average time duration over which a radionuclide exists in a particular form. This time being defined as the 'life-time' or mean life of the radionuclide, and is the reciprocal of the decay constant thus:

$$\tau_{(radionuclide)} = 1/\lambda_{(radionuclide)} \qquad \text{(Eq. 3)}$$

Where:

τ = The mean life or lifetime of a radionuclide (y).

λ = The decay constant for a given radionuclide which can also be defined as the probability of radioactive decay of a given nuclei (per/year). The decay constants and life times for the radioisotopes considered is given in Table I.

Table I. Life Times (y)

Radioisotope	Half-life (y)	λ	Life-time (y)
Am-241	432	1.6E-03	624
Cs-137	30	2.3E-02	44
Co-60	5	1.3E-01	8
Pu-239	24065	2.9E-05	34726
Pu-241	14	4.8E-02	21
H-3	12	5.7E-02	18
U-234	247000	2.8E-06	356421
U-235	710000000	9.8E-10	1024531025
U-238	4500000000	1.5E-10	6493506494

Using the life-time value in a formula to calculate the equivalency factor will greatly influence the result and it is clear that the long lived isotopes (uranium) will be calculated as being the most serious.

The author has equated the half-life to a reference period of 100 years and used this in the EF formula to overcome this in-balance. This period is compatible with the approach adopted in other life-cycle assessments. To calculate the % decayed the standard equation for radioactive decay is used:

$$A(t) = A(0).e^{-\lambda t} \quad \text{(Eq. 4)}$$

Where:

A(t) = activity at some time in the future (100 years in this case)

A(0) = activity at the time of discharge

λ = the decay constant

t = time (100 years)

Table II gives values derived for the nine radioisotopes chosen to demonstrate this research.

Table II. % Decay in the Environment (100 years)

Isotope	λ	Time (years)	Activity at release A(0)	Activity at time A(t)	Amount decayed in 100 years	% decay
Am-241	1.6 E-3	100	50	4.26 E+1	7.39 E+0	14.78
Cs-137	2.3 E-2	100	50	5.01 E+0	4.5 E+1	89.97
Co-60	1.3 E-1	100	50	1.13 E-4	5.00 E+1	99.99
Pu-239	2.9 E-5	100	50	4.99 E+1	1.45 E-1	0.29
Pu-241	4.8 E-2	100	50	4.11 E-1	4.96 E+1	99.17
H-3	5.7 E-2	100	50	1.67 E-1	4.98 E+1	99.66
U-234	2.8 E-6	100	50	5.00 E+1	1.4 E-2	0.03
U-235	9.8 E-10	100	50	5.00 E+1	4.9 E-6	0.00001
U-238	1.5 E-10	100	50	5.00 E+1	7.5 E-7	0.000001

Dose Coefficient Factors (DCF) used in this paper are reproduced in Table III.

Table III. Dose Coefficient Factors

Radioisotope	DCF for Inhalation (Adult Medium Acting) (Sv Bq^{-1})	DCF for Ingestion (Adult) (Sv Bq^{-1})
Am-241	4.2 E-5	2.0 E-7
Cs-137	9.7 E-9	1.3 E-8
Co-60	1.0 E-8	1.4 E-9
Pu-239	5.0 E-5	2.5 E-7
Pu-241	9.0 E-7	4.8 E-9
H-3	4.5 E-11	4.2 E-11
U-234	3.5 E-6	4.9 E-8
U-235	3.1 E-6	4.7 E-8
U-238	2.9 E-6	4.5 E-8

The 19 parameters identified above are summarised in Table IV. , which also identifies whether each parameter is considered to represent an environmental fate or effect and how dose coefficient factors relate to each of these parameters.

Table IV. Parameters and the Relationship Between Fate, Effect and DCF

Parameter	Effect or Fate	Covered by DCF	Method by which the parameter will be measured in the EF formula
1	Fate	No.	Life-time based on half-life of radionuclide.
2	Fate	No.	The total amount of activity released (Bq)
3	Effect	Yes DCF take into account specific activity.	Covered by DCF.
4	Effect	Yes DCF take into account MeV.	Covered by DCF.
5	Effect	Yes DCF take into account LET.	Covered by DCF.
6	Effect	Yes DCF take into account radiation type.	Covered by DCF.
7	Effect	No.	Ozone creation from routine discharges has been shown to be trivial. This parameter is not applicable.
8	Fate	No.	Bioaccumulation potential of stable isotope.
9	Effect	Yes DCF take into account the bioaccumulation in humans.	Covered by DCF.
10	Effect	Yes DCF take into account the biological half-life of radioisotopes in humans.	Covered by DCF.
11	Fate	No.	Covered by parameter 1.
12	Effect	Yes DCF take into account radio-sensitivity (humans only).	Covered by DCF.
13	Effect	Yes DCF take into account of toxicity.	Covered by DCF.
14	Fate	No.	Chemical behavior characteristics of the stable isotope
15	Effect	Yes DCF take into account reactions inside the human body.	Covered by DCF.
16	Effect	Yes DCF take into account biological behavior in humans.	Covered by DCF.
17	Fate	No.	Not applicable. It is assumed that there are no unusual properties associated with the land, air of freshwater receiving media around Aldermaston.
18	Fate and effect	No. This parameter is only valid if monitoring data reveals that the health of ecosystems is being threatened	Not applicable. Although the presence of other hazardous substances will impact upon species, this is only of interest if the health of ecosystems is being studied and a correlation between health and radionuclide releases is being sought.
19	Fate and effect	Yes DCF take into account solubility inside the human body.	The solubility of the stable isotope will be used.

From Table IV it is clear that a number of parameters are included in the biokinetic model used to determine DCF values [3]. In addition the following parameters are identified as being measurable and having a direct influence on environmental fate and effect:

- Life-time (years) (Parameter 1)
- Total activity (Bq) (Parameter 2)
- Bioaccumulation potential (ranked as either High, Medium or Low) (Parameters 8 and 9)
- Chemical behavior and toxicity (measured by environmental benchmarks and ranked as either High, Medium or Low) (Parameters 13 and 14)

- Solubility (based on behavior of in water and ranked as either High, Medium, Low or Insoluble) (Parameter 19)

To derive a formula for calculating the EF these last three parameters are scored as follows: High = 3; Medium = 2; Low = 1; None/Insoluble = 0. For parameters for which there is no data a score of 1 is given as a default value. Data to guide the scoring is taken from Croner’s database on hazardous chemicals [4] and where there is no data for the specified radioactive nuclide a stable analogue is used instead. The justification for the Toxicity (T), Bioaccumulation (B) and Solubility (S) scores is given in Table V.

Table V. Toxicity, Bioaccumulation and Solubility Scores

Radioisotope	Stable Analogue	Environmental Information (taken from reference 4)	B	T	S
Am-241	Lead/ Bismuth	High bioaccumulation for most organisms, highly toxic and insoluble.	3	3	0
Cs-137	Potassium	Low bioaccumulation potential, low ecotoxicity and freely soluble in water.	1	1	3
Co-60	Cobalt/ Nickel	Low bioaccumulation potential, low toxicity and insoluble.	1	1	0
Pu-239	Lead	High bioaccumulation for most organisms, highly toxic and insoluble.	3	3	0
Pu-241	Lead	High bioaccumulation for most organisms, highly toxic and insoluble.	3	3	0
H-3	Hydrogen / Helium	Tritium when organically bound bioaccumulates up the food chain. Tritium follows the hydrological cycle penetrating all components of the biosphere. It will exchange with non-radiological isotopes of hydrogen (protium and deuterium). Hydrogen is not chemically toxic. It dissolves easily in water.	2	0	3
U-234	Uranium/ Lead	High bioaccumulation potential, highly toxic and chemically reactive. Insoluble in water.	3	3	0
U-235	Uranium/ Lead	High bioaccumulation potential, highly toxic and chemically reactive. Insoluble in water.	3	3	0
U-238	Uranium/ Lead	High bioaccumulation potential, highly toxic and chemically reactive. Insoluble in water.	3	3	0

The Equivalency Factor (EF) is based on a combination of fate and effect. The effect part of the formula is made up of the relevant DCF value and fate is based upon the combination of life-time, bioaccumulation, chemical toxicity and solubility. The total activity is equivalent to the mass in conventional LCA impact determinations. The EF formula is derived thus:

EF = Effect x Fate

EF = Effect in the receptor x Fate in the Environment

EF = DCF value x Fate in the environment

EF = DCF value x (B + T + S) x Life-time value over a 100 years (Eq. 5)

Where:

B = bioaccumulation score

T = chemical toxicity score

S = Solubility score

The overall impact is calculated thus:

$$Sji = MiQji \quad \text{(Eq. 1)}$$

Where:

Sji potential contribution to environmental irradiation impact j from discharge i

Mi Environmental quantity (total activity Bq)

Qji characterisation factor (impact potential or equivalency factor) for radioactive substance i to environmental irradiation impact category j

Separate Equivalency Factors for discharges to water and air are derived and given in Table VI and Table VII.

Table VI. Equivalency Factors for Releases to Water

Radioisotope	DCF (Ingestion)	B	T	S	Life-time value	EF
Am-241	2.0 E-7	3	3	0	14.78	1.77 E-5
Cs-137	1.3 E-8	1	1	3	89.97	5.85 E-6
Co-60	1.5 E-9	1	1	0	99.99	2.8 E-7
Pu-239	2.5 E-7	3	3	0	0.29	4.35 E-7
Pu-241	4.8 E-9	3	3	0	99.17	2.86 E-6
H-3	4.2 E-11	2	0	3	99.66	2.09 E-8
U-234	4.9 E-8	3	3	0	0.03	8.82 E-9
U-235	4.7 E-8	3	3	0	0.00001	2.82 E-12
U-238	4.5 E-8	3	3	0	0.000001	2.7 E-13

Table VII. Equivalency Factors for Releases to Air

Radioisotope	DCF (Inhalation)	B	T	S	Life-time value	EF
Am-241	4.2 E-5	3	3	0	14.78	3.72 E-3
Cs-137	9.7 E-9	1	1	3	89.97	4.36 E-6
Co-60	1.0 E-8	1	1	0	99.99	2 E-6
Pu-239	5.0 E-5	3	3	0	0.29	8.7 E-5
Pu-241	9.0 E-7	3	3	0	99.17	5.36 E-4
H-3	4.5 E-11	2	0	3	99.66	2.24 E-8

Radioisotope	DCF (Inhalation)	B	T	S	Life-time value	EF
U-234	3.5 E-6	3	3	0	0.03	6.3 E-7
U-235	3.1 E-6	3	3	0	0.00001	1.86 E-10
U-238	2.9 E-6	3	3	0	0.000001	1.74 E-11

CONCLUSIONS

- Equivalency factors have been developed that allow radioactive substances to be included in the framework of LCA.
- Radioactive discharges can be plotted and compared graphically.
- LCA methodology can be applied at nuclear sites to improve reporting in the EMS.
- This methodology will allow radioactive substances to be more appropriately assessed so that disproportionate cost and resources are not applied to reduce radiological concentrations at the expense of other environmental impacts.

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