How to correctly choose the list of relevant radionuclides to assess dose uptake by workers?

G. Genard*, B. Gonze, D. Hulhoven and S. Vanderperre

Radwaste and Decommissioning, Tractebel ENGIE
Ariane avenue 7, B1200 Brussels – Belgium

* *Phone: +32 2 773 88 59 – Fax: +32 2 773 89 00 – gilles.genard@tractebel.engie.com*

1. Introduction

Both for day to day activities as for specific projects in a Nuclear Power Plant, ALARA studies and shielding calculations have to be performed. Such studies are based on several input parameters such as the work position, the source and the existing shielding geometries and dose rates.

For existing situations, the associated dose rate can be determined based on measurements in the field. However, for situations related to accidental conditions or for new build projects, no measurement data are available. Hence, a radionuclide source term is determined based on validated models. Then, dose rates can be determined from this source term.

A radionuclide source term is a list of all possible radionuclides that can occur for the case of interest and links these radionuclides with a certain activity level. This list can include more than 1000 radionuclides of which only a small fraction have a significant contribution to the dose rate. Hence, the time to calculate the dose rate can be significantly reduced by selecting those radionuclides that contribute to the dose rate whilst neglecting those that represent an insignificant contribution.

This paper gives an overview of the methodology, developed by Tractebel ENGIE, for the reduction of the initial source term to a manageable source term. In the methodology, it was taken into account that a (slightly) conservative approach for the source term was guaranteed.

This methodology was used for several projects in the past. A short summary of some applications for the reduction of the source term is given.

2. Methodology

The methodology is based on the use of three screening steps. The first two screening steps identify the radionuclides to neglect, based on radiological information such as activity and gamma ray energies. The third screening step adds some extra radionuclides to avoid neglecting at the first and second steps, some radionuclides with relatively high energy lines when shielding layers are added to the geometry.

The described methodology uses the activities defined in the initial source term '*S*'. Radiological properties of the radionuclides '*s*' from *S* can be those obtained from any relevant library for radionuclides, such as the ICRP-38 publication [1], the ICRP-107 publication [2] or the ones used by the NEA Nuclear Data Information System JANIS [3].

The data that are needed are:

- The gamma lines for each radionuclide;
- The branching factor of each gamma line.

In the following paragraphs, the different screening steps are discussed.

2.1 *Screening 1 – Relative activity of the radionuclides*

In the first screening, the list is reduced based on the activity of the radionuclides, A_i. It is considered that only those radionuclides with sufficient activity contribute significantly to the total dose rate. In this step, radionuclides are selected based on their order of magnitude ‘*N*’.

The factor *N* is determined to ensure that the sum of the activities of all radionuclides with an activity in the order of magnitude of at least *N* represent at least 99.99% of the total activity of the initial source term *S*. The selected radionuclides form together the reduced source term after the first screening, ‘*K*’. A specific radionuclide in this list is denoted radionuclide ‘*k*’. This is detailed in the flowchart of Figure 1.

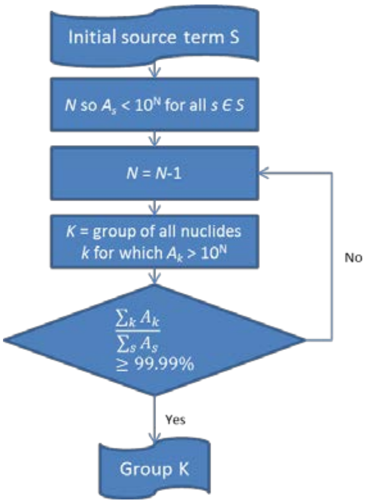

Figure 1 - Flowchart representing the first screening. Source term *K* is determined based on the activity levels of the radionuclides in source term *S*.

It is worth mentioning that the activities A_i to be considered here can take different forms, such as absolute activities (in Bq), volume activities (in Bq/m³) or mass activities (in Bq/g), since only their relative values are compared.

2.2 *Screening 2 – Relative weight of the radionuclide*

After the second screening, the source term *K* is, based on the relative weight of the radionuclides *k*, reduced to source term ‘*L*’.

The weight of the radionuclide k (P_k) in terms of dose rate is determined based on the activity of the radionuclide A_k, the photon energies of the radionuclide $E_{k,j}$ and the branching factors of these photon energies $I_{k,j}$:

$$P_k = \sum_j A_k \cdot E_{k,j} \cdot I_{k,j} = \sum_j Q_{k,j}$$

In this formula, $Q_{k,j}$ is defined as the energy weight of an energy line *j* within the group *K*.

The energies $E_{k,j}$ represent a group of photon energies of radionuclide k. Gamma energies associated to a negligible energy weight Q_{kj} can be neglected in the weight calculation. The selection of this group of (remaining) energies '*J*', for a radionuclide k, is performed based on (as illustrated on the flowchart of Figure 2):

- The most impacting energies with a total representation of at least 90% of the cumulated energy weights;
- The definition of the energy '*m*', representing the maximum energy of the previously determined group;
- Addition of all energies higher than energy *m* and with an energy weight above 5%.

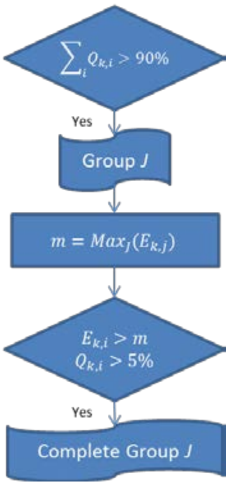

Figure 2 - Flowchart representing the selected energies for the second screening.

Afterwards, the branching factor $I_{k,j}$ of each energy in group *J* of the radionuclides *k* is rescaled to 100% and P_k is calculated.

The value P_k should be interpreted as an indication of the contribution of a specific radionuclide to the dose rate if no shielding is present.

Note that the product $A_k \cdot E_{k,j} \cdot I_{k,j}$ (in percentage, not necessarily normalised to the group *J*) is directly given by the dose rate calculation software MicroShield [4] when selecting one single radionuclide as source term and is called in that software the percentage of energy activity (specific to the chosen library), which eases the work.

The relative weight F_k of each radionuclide *k* is then determined based on the ratio of the weight P_k of the radionuclide and the sum of the weights of all radionuclides in source term *K*.

Subsequently, the screening consists in selecting only those radionuclides *k* that have a relative weight equal to or above 0.1%. These radionuclides are added to the short list '*L*' and a radionuclide of this group is denoted as radionuclide *l*. This is detailed in the flowchart of Figure 3.

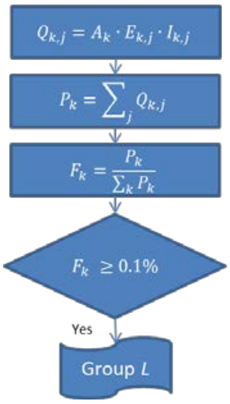

Figure 3 - Flowchart representing the second screening. Source term *L* is determined based on the relative weight of the radionuclides in source term *K*.

2.3 Screening 3 – Importance of gamma ray energy

In the third screening, the source term *L* is extended to take into account those radionuclides *k* with higher energy levels but which were excluded in screening 2. This is performed to take into account that, if more shielding layers are added, the relative contribution of high energy rays to the dose rate becomes more important. This is explained by the fact that radionuclides having a high activity and low gamma energies will be more attenuated by the shielding layers than radionuclides with lower activity but higher gamma energies. Consequently, it could occur that a radionuclide which was not selected during the second screening can still have a non-negligible influence on dose rate after addition of shielding layers in the geometry.

To determine the energy threshold, a photon energy '*M*' is defined based on:

- Q_{max}, the maximum energy weight amongst all the energy lines for all radionuclides *l* within group *L*;
- The group '*H*' that consists of all photon energies '*h*' (selected the same way as to determine the energy group *J* in the second screening) of all radionuclides *l* within group L such as that $\frac{Q_{max}}{100} \leq Q_{l,h} \leq Q_{max}$;
- The energy *M* is then defined as the second highest energy of this group *H*.

As a last step, all radionuclides within group *K* (that were not selected in the group *L* following the second screening) with at least one energy that is equal to or higher than *M* is added to the source term *L*. The arbitrary choice of the second highest energy of group *H*, instead of the highest, increases the probability of a radionuclide in source term *K* to be selected. This is detailed in the flowchart of Figure 4.

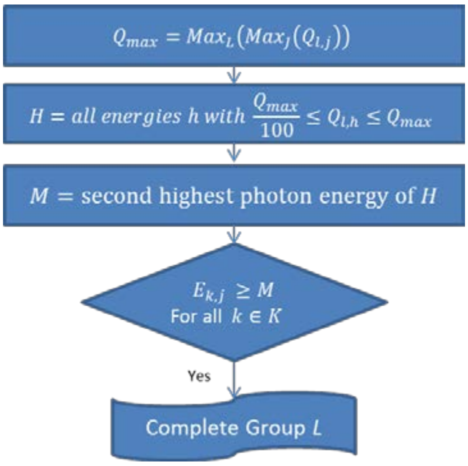

Figure 4 - Flowchart representing the third screening. Radionuclides from source term *K* are added to the source term *L* based on their radiation energies.

3. *Applications*

3.1. CFVS

Based on severe accident studies after the accident at the Fukushima nuclear power plant, it was decided to install a Containment Filtered Venting System (CFVS) for all Belgian nuclear power plant entities. The purpose of this CFVS is to depressurize the reactor building in case of uncontrolled pressure rise during post-accident conditions, by venting the containment. Before the release to the environment, the vented gases pass through a filter to capture the different species of radioactive contaminants and reduce the radiological impact to the surroundings.

Due to the limited space inside the nuclear facilities, it was decided to build a new building for each entity, which will house the CFVS filter, in close proximity of the reactor building. However, for some of the units, the CFVS building will not be in contact with the reactor building and a gallery will be constructed to house the venting line between the reactor building and the CFVS building.

Due to the specific use of this equipment during post-accident conditions, limited remote manual intervention will be required for operating the CFVS installation. Consequently, a study was performed to assess the required concrete wall thickness of the building and the gallery in order to limit as low as reasonably achievable the dose rates resulting from the venting line.

The initial source term

For each power plant (Doel and Tihange), a conservative accident source term was determined using the severe accident modelling softwares MELCOR [5] and IODE (ASTEC) [6]. Both initial source terms featured 1038 radionuclides and covered 8 venting periods. For each radionuclide, an activity level, expressed in Bq/s, was determined.

As a different source term was determined for Doel and Tihange, the above discussed methodology had to be independently applied for each site. However, to incorporate additional conservatism, a single combined source term for Doel and Tihange was used for calculating the concrete wall thickness.

First screening

The first screening is performed on an individual level for each venting event. Hence, in total, the first screening was performed 8 times per entity. It was ensured that, for each venting period, the criterion of 99.99% of the total activity was complied with.

As different venting events produce different radionuclide lists, a single list, combining the radionuclide lists *K* of all the individual venting events, was defined. Based on the first screening, a source term *K* with 60 radionuclides and 28 radionuclides was determined for Doel and Tihange, respectively. This corresponds respectively to 6% and 3% of the radionuclides in the initial source term.

Second screening

For the second screening, only the most conservative venting event was taken into account.

The selection was performed for both the Doel and Tihange short lists *K* on an individual level. Based on this step, the source terms of Doel and Tihange were reduced to 23 radionuclides and 15 radionuclides, respectively. These represent the source terms *L* in the methodology.

Third screening

For both source terms, the energy *M* was determined. A separate value per source term was obtained but, except for those radionuclides already selected in source term *L*, no radionuclides of source term *K* corresponded to the criterion.

Consequently, the final short lists of Doel and Tihange consist of 23 and 15 radionuclides, respectively. This corresponds to 2.2% and 1.5% of the radionuclides in the initial source term, respectively.

As both source terms were combined, a short list of, in total, 31 radionuclides was defined. Hence, only 3% of the radionuclides were identified to have a significant impact on the dose rates outside the gallery.

3.2. EOF

One of the actions of the Belgian Stress Tests following the Fukushima accident was to build a new Emergency Operation Facility (EOF) for the Tihange nuclear power plant. This facility will be built on the site of the power plant. As the function of the EOF is to support the management of emergency response after a nuclear accident in one or more of the nuclear entities on site, radioactive sources are to be expected in the vicinity of and inside the building.

The radioactive source that could be responsible for the exposure of workers inside the facility is identified as the atmospheric contamination around the building after the actuation of the filtered vent of (at least) one nuclear unit impacted by a severe accident. This source contributes to the dose rate inside the building in two-fold:

- Irradiation through the external walls;
- Contribution from the contaminated atmosphere inside the building. This contamination is reduced thanks to HVAC filters that treat external atmospheric contamination before supplying the air to the habitable zones of the building. Nevertheless, the HVAC filters constitute an additional irradiation source.

At the design phase of the building, keeping the occupational dose as low as reasonably achievable was set as a goal and an effective dose rate criterion was imposed in order to size the external walls (on the basis of the external contaminated atmosphere) and the internal walls (on the basis of the HVAC filters). This criterion was set to keep the effective dose rate below 1 mSv/h at 50 cm from the walls, which is seen as the average distance between the walls and a worker moving inside the building, and at 1.30 m above ground level, which is representative of the personal dosimeter height.

As for the CFVS application, the list of radionuclides to be considered for the dose rate calculations is large and a selection of the most relevant ones is needed to make calculations manageable. The methodology presented in this work has been separately applied for the two wall sizing. The example of the contribution to the dose rate via the irradiation through the external walls is detailed in the following sections.

The initial source term

In order to assess the source term around the EOF, the output of the filtered vent has been calculated the same way as for the CFVS (Tihange case), the difference being that only the fraction which is not absorbed in the CFVS installation is taken into account (mainly noble gases). Due to the distance between the CFVS installation and the EOF, a dispersion of the released activity occurs. It was considered that a uniform distribution of the activity in the volume between the CFVS stack and EOF surroundings occurs (see Figure 5).

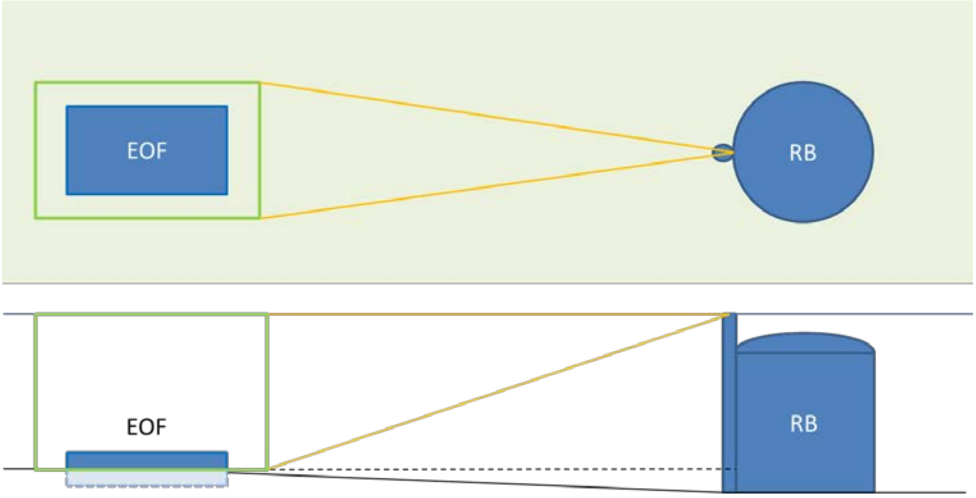

Figure 5 - Activity spread between the CFVS stack and the EOF. In green, the volume of air taken into account surrounding the EOF building. In yellow, the volume of air taken into account between the CFVS stack and the EOF building.

A 1038 radionuclides source term, determined in function of time after initiation of the first venting, was then obtained under the form of an activity concentration, expressed in Bq/m^3, integrated during 3 minutes. It is worth mentioning that the natural leak occurring between two venting events has also been considered and added to the venting event contribution. For the calculation of wall thicknesses, the highest activity concentration in time is used.

First screening

Based on the first screening, a source term *K* with 26 radionuclides (2.5% of the radionuclides of the initial source term) was sufficient to enable reaching the criterion of 99.99% of the total activity. It can be pointed out that, in practice, 26 radionuclides can already be handled. Nevertheless, for the exercise, the next screening steps have been applied.

Second screening

The second screening, based on the weight of radionuclides from source term *K*, has enabled to shorten the list down to 8 radionuclides, which represent source term *L*.

Third screening

In order to ensure that no radionuclides featuring relatively high gamma rays have been forgotten, the third screening was applied.

Based on the determined energy *M*, 3 radionuclides which were not yet selected from source term *K* were added to the source term *L*.

Hence, the final short list consists of 11 radionuclides. This means that only 1.1% of the radionuclides were identified to have a significant impact on the dose rates to determine the external walls thickness.

4. Discussion

4.1. Influence of the screenings on the calculated dose rate

Based on the CFVS case, the influence of the source term reduction was determined. The following points give an indication of the sensitivity of the different screening steps. This is performed by means of MicroShield calculations based on a representative model.

Screening 1 – 'N-1'

Based on the source term of the Tihange nuclear power plant, the change in factor *N* to *N-1* (meaning considering radionuclides with an activity one order of magnitude smaller) for the screening adds 15 radionuclides to the list. However, these 15 radionuclides only represent an addition of 0.0012% in activity.

The total extra dose rate due to these 15 radionuclides was determined to be 0.018%. Hence, these radionuclides have no significant contribution in the total dose rate. Based on this result, it can be decided that the first screening does not exclude important radionuclides.

Screening 2 and 3 – With or without screening

In the second screening, radionuclides are selected based on their relative weight. A check of the difference in calculated dose rate between *K* and *L* source terms was performed.

The source term of the Tihange CFVS project was used. A dose rate simulation, identical to the simulation for screening 1, was carried out. Two calculations were performed:

- A first one including all the radionuclides of source term K (28 radionuclides);
- A second one considering only the selected radionuclides in source term L (15 radionuclides) after screening 2 and 3.

The 13 radionuclides that were excluded in screening 2 represent a dose rate fraction of 0.7%. Consequently, the conservatism of the calculation (based in particular on a conservative source term) is not influenced by this step.

4.2. Quality of the methodology

Based on the previous impact analysis of the methodology, no significant influence of the screening was detected on the calculated dose rate. The difference between the calculations with or without source term reduction is less than 1% for the considered case.

Due to the conservatism of the initial source term, the calculated dose rates remain conservative after the reduction of the source term. Even in case of less conservative source terms, the methodology developed here provides fairly good results. It is worth noting that the models (geometry of the source and the shielding) are usually also defined in a conservative way.

If a simulation is performed for the 1038 radionuclides (in the case of the two presented applications) in the initial source term, this would not be manageable. The reduction of the source term from 1038 radionuclides to 31 radionuclides (CFVS) and 11 radionuclides (EOF) limits the required simulation time a lot, without significantly influencing the calculated dose rate.

It should however be noted that if, due to new input parameters, the source term would be altered, a new screening has to be performed as the methodology strongly depends on the activities of the radionuclides in the source term.

5. Conclusion

In this paper, a methodology enabling to shorten the list of radionuclides in a source term initially composed of numerous radionuclides, down to a manageable number, is presented. This is very useful and even necessary when dose rates to workers have to be assessed from a source term including a huge number of radionuclides; for instance for the assessment of dose uptake in post-accident conditions, on the basis of emergency operating procedures.

Two applications of this methodology have been discussed, where the list of radionuclides has been decreased to 3% and 1% of the initial source term.

A sensitivity analysis has been performed in order to assess the impact of this methodology on the dose rate calculation. Even if a slight underestimation can be seen (< 1%), the quality of the methodology is good, in addition of its efficiency. When the dose or dose rate calculation does not involve conservatisms (neither on the source term nor on the calculation model), it is advised to add a small conservative factor.

6. *References*

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