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Radiological Activity of Release: A Surrogate Consequence Measure for Assessment of Risk of Severe Accidents

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Abstract

Probabilistic Safety Assessments (PSAs) are performed to (a) identify potential vulnerabilities to severe accidents, (b) demonstrate compliance with regulatory safety requirements, and (c) evaluate safety performance with respect to potential procedural and/or hardware improvements. Typically, the identification of potential containment vulnerabilities to severe accidents is based on the results of Level-2 PSAs (e.g., conditional containment failure probability [CCFP] and large early release frequency [LERF]). However, the determination of thresholds of significance using these measures poses difficulties. In addition, an assessment of risk-beneficial plant safety improvements using Level-2 PSA-based measures cannot be achieved since these attributes do not provide in all instances integrated measures against which the changes in plant risk can be effectively evaluated. A demonstration of the relevance of using the environmental release of radiological activity as an appropriate consequence measure in an integrated risk calculation of severe accidents for assessment of plant safety performance is provided. Furthermore, a discussion of the relationship of radiological activity associated with various radionuclides to other more recognized consequence measures (e.g., early fatality, latent fatalities, etc.) is provided. Calculations for a reference plant show that the use of different consequence measures leads to conclusions that are very similar to one another regarding risk assessment and plant performance; therefore, justifying the use of radiological release activity as an effective yet easy to calculate measure of severe accident consequences.

1. Background

Probabilistic Safety Assessments (PSAs) are performed for nuclear power plants for a number of different purposes, including identification of potential vulnerabilities to severe accidents, demonstration of compliance with regulatory safety requirements, and evaluation of safety performance with respect to potential procedural and/or hardware improvements. A Level-1 PSA estimates the frequency of core damage events at the plant based on the plant configuration at the time of core damage, given assumptions and inputs regarding initiating event frequencies and hardware or human failure probabilities. A Level-2 PSA estimates the radiological releases to the environment (i.e., source terms) based on the Level-1 PSA results and an analysis of the post-core damage accident progression and radiological release and transport, while a Level-3 PSA would calculate off-site consequences (e.g., health, economic, etc.) based on the radiological releases that are estimated as part of the Level-2 PSA analyses.

PSAs performed for nuclear power plants often do not progress beyond the Level-2 stage of the analysis; therefore, omitting an explicit and plant-specific treatment of off-site consequences of severe accidents. This leads to questions regarding what figure-of-merit for severe accident consequence or risk can be used in the evaluation of Level-2 PSA results. For example, it may be required to determine whether a contemplated hardware modification or procedural augmentation would result in a worthwhile improvement in plant safety, or one may simply wish to identify what proportion of current plant risk can be attributed to a particular initiator, hardware failure, or class of accidents.

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One possible measure of severe accident consequence, as exemplified in Reference [1] consists of the magnitude of activity (in units of Becquerel) released to the environment over the course of an accident defined as disintegration per second per gram or Becquerel per gram of a particular isotope as:

$$Activity\,[Bq/gr] = \lambda \bullet n = \frac{0.6931}{T_{1/2}} \bullet \frac{N}{A} \tag{1}$$

where λ is the radioactive decay constant (per second), n is the nuclide concentration, $T_{½}$ is the half-life ($\equiv \ln 2/\lambda = 0.6931/\lambda$) in seconds, N is the Avogadro number (= 0.6025×10^{24}), and A is the atomic weight in grams.

The product of this consequence measure with the accident frequency (per year) can be obtained to arrive at a measure of plant risk in units of Becquerels per year, namely:

$$R_c = \sum_j \sum_d \sum_s [f_j \cdot P(j|d)] \cdot P(d|s) \cdot C(s|c) \tag{2}$$

where R_c is the risk of consequence measure c (consequence per year, in this case, Bq per year); f_j is the frequency of initiating event *"j"* (per year); *P(j|d)* is the conditional probability that initiating event *"j"* will lead to plant damage state *"d"*; *P(d|s)* is the conditional probability that plant damage state *"d"* will lead to source term (release) *"s"*; and *C(s|c)* is the expected value of the conditional consequence measure *"c"* (e.g., activity), given the occurrence of source term (release) *"s"*.

Even though activity does not have a direct connection to offsite consequences of severe nuclear accidents, PSA results employing activity of release as the figure-of-merit can be compared with those estimating offsite consequences such as early fatalities or latent cancers using data from Level-3 PSA analysis tools. It is the objective of this paper to demonstrate that the insights obtained through Level-2 PSA analysis using a calculation of risk of activity of release lead to the same qualitative insights into plant risk and containment performance that would be obtained with a full Level-3 PSA. Therefore, using this approach can avoid the introduction of additional uncertainties that result from Level-3 PSAs into the overall risk quantification and hence serving as a useful alternative for risk-benefit studies and other PSA applications.

2. Approach

In order to illustrate the impact of different measures of plant risk, a reference PWR Level-2 PSA is used. The Level-2 PSA model for this reference plant was modified to perform integrated calculations of plant risk given any defined measure of a conditional consequence. This PSA model results in several dozen unique Level-2 sequences categorized into release bins, including steam generator tube ruptures, containment bypasses or unisolation, containment rupture (e.g., due to overpressure), filtered containment venting, and intact containment (involving technical specification-based containment leakage), among others. Sequence frequencies are assumed to be typical of Level-1 PSA results and an event tree accounting for Level-2 phenomena impacting event progression and containment performance, with separate analyses quantifying the likelihoods of direct containment heating, hydrogen combustion, and other events.

In the PSA model, non-noble gas activity of release is the primary measure of accident consequence employed. Noble gases are excluded from this measure of activity because they have relatively short half-lives and little biological persistence, and are therefore expected to be proportionately less consequential than other radionuclides that are in either gaseous or aerosol forms. Moreover, many of the release categories entail the release of all or most of the initial inventory of noble gases, which are not filtered, scrubbed, or retained in the containment and/or engineered systems. Therefore, inclusion of noble gases in the primary risk measure would tend to drown out the contributions of often smaller but more relevant radionuclides (e.g., iodine, cesium, tellurium, etc.).

2.1 Risk-Significant Nuclides

Large numbers of radionuclides build up inside the reactor fuel during plant operation. However, of this large number of different nuclides forming the initial core inventory, many of them will have very short half-lives and/or low consequences. Therefore, it is possible to significantly restrict the number of

nuclides considered in PSA calculations while retaining an accurate estimate of severe accident risk. The present study takes into account 60 individual radionuclides representing 25 unique elements. Initial inventories of the nuclides in this list were obtained via a combination of scaling generic ORIGEN calculations from a 3412 MWt PWR, and (where obtainable) plant-specific values from the last available core load. Calculation of the activity of release in the Level-2 PSA model accounted for radioactive buildup and decay of each radionuclide (accounting for any parent-daughter decay chains) between the time of reactor shutdown and the time at which release to the environment starts.

2.2 Consequence Weighting Factors

For purposes of the present study, a site-specific study is not performed in order to directly calculate offsite health effects from the calculated Level-2 PSA source terms. Instead, an approach is used which allows estimation of offsite health effects using the activity of release for each nuclide and an appropriately chosen set of consequence weighting factors. In a previous study performed in support of a definition of large early release [2], MACCS2 calculations for a different reference plant were employed to develop weighting factors which can be applied to such a calculation. The weighting factors here are defined as:

$$W_{k,EF} = \frac{\text{Early fatalities from release at t = 1 h of 100\% of core inventory of nuclide } k}{\text{Total activity of nuclide } k \text{ at t = 1 h}} \quad (3a)$$

and

$$W_{k,LC} = \frac{\text{Latent cancers from release at t = 1 h of 100\% of core inventory of nuclide } k}{\text{Total activity of nuclide } k \text{ at t = 1 h}} \quad (3b)$$

These weighting factors have units of fatalities per Becquerel and cancers per Becquerel, respectively. In the referenced study, early fatalities were defined as those occurring within 16 km of the plant, while latent cancers were calculated up to 700 km distance and included both early and late effects. With these definitions of weighting factor, resulting in the calculated values listed in Table 1, the offsite health consequence of the release of a fraction s_{jk} of nuclide k from sequence j at time T_j can be calculated using the formula:

$$\text{Health consequence from nuclide } k \text{ in sequence } j = c_{jk} = s_{jk} W_k \left(\frac{N_k(t_j)}{N_k(1\,\text{h})} \right) \quad (4)$$

where $N_k(t)$ is the calculated whole-core inventory of nuclide k at time t, accounting for buildup and decay since reactor shutdown.

The following most relevant assumptions were made in the construction of this set of weighting factors:

- Initial inventories of all nuclides in the core were scaled from reference calculations for a 3578 MWt BWR [2].
- A single source term was analyzed, comprising 100% release of the inventory of all nuclides in the core.
- Release was assumed to begin one hour after reactor shutdown and to occur at ground level.
- No credit was assigned for emergency or long-term protective actions.
- Various assumptions were made concerning specific site data and parametric inputs such as radiation protection factors.

In general, it is expected that a different set of consequence weighting factors would be calculated if the initial core inventory, site, and release type were to be varied. Furthermore, it is not necessarily the case that health effects would scale linearly with the magnitude of activity released, as implied by Equation (4). However, to avoid extensive consequence calculation with their attendant uncertainties, and since the approximations as implied by Equations (3) and (4) have been found to be acceptable for determination of thresholds and risk-benefit studies, this approach is considered adequate for the present application.

3. Results

3.1 Importance of Individual Nuclides to Risk of Radiological Releases

As evaluated for any given measure of offsite consequence, the consequence for an individual core damage sequence equals the sum of the consequence contributions from each radionuclide. Therefore, the component of risk derived from this consequence measure from one radionuclide divided by the total risk from all of them can be viewed as the relative importance of that nuclide to plant risk of release. That is,

$$\text{Relative risk contribution from nuclide } i = R_i = \frac{\sum_j f_j c_{ji}}{\sum_j \sum_k f_j c_{jk}} \qquad (5)$$

where c_{jk} is the conditional consequence due to nuclide k from sequence j (according to Equation (4)) and f_j is the frequency (per year) of Level-2 PSA sequence j.

Table 1 Radiological Consequence Weighting Factors (from Reference [2])

Nuclide	Weighting Factor For Early Fatalities (per PBq)	Weighting Factor For Latent Cancers (per PBq)
Americium (Am)	0	4.2E+03
Antimony (Sb)	6.4E-05	3.2E-02
Barium (Ba)	2.8E-03	5.0E-01
Cerium (Ce)	5.4E-03	1.9E+00
Cesium (Cs)	6.5E-03	5.3E+01
Cobalt (Co)	0	5.9E+01
Curium (Cm)	5.2E-01	3.0E+02
Iodine (I)	1.9E-03	2.4E-02
Krypton (Kr)	9.9E-05	1.6E-03
Lanthanum (La)	3.9E-03	3.4E-02
Molybdenum (Mo)	1.6E-03	5.1E-02
Niobium (Nb)	5.5E-03	1.0E+00
Neodymium (Nd)	9.1E-05	1.2E-01
Neptunium (Np)	1.2E-03	3.3E-02
Plutonium (Pu)	1.5E-02	2.3E+02
Praseodymium (Pr)	1.1E-03	9.1E-02
Rhodium (Rh)	3.8E-08	1.1E-02
Rubidium (Rb)	0	9.9E-02
Ruthenium (Ru)	4.7E-03	2.2E+00
Strontium (Sr)	2.5E-03	2.4E-01
Technetium (Tc)	1.6E-08	9.3E-04
Tellurium (Te)	8.9E-03	1.3E-01
Xenon (Xe)	0	7.1E-04
Yttrium (Y)	2.8E-03	2.1E-01
Zirconium (Zr)	5.3E-03	1.9E+00

Relative risk contributions are calculated using Equation (5) for the reference plant and presented in Tables 2 and 3. The fractions of total offsite risk attributable to each element for two representative categories of core damage sequence are shown: (a) an SGTR with the break below water (the most frequency-dominant large early release sequence), and (b) a filtered containment venting scenario (the most frequency-dominant late release sequence). The possible measures of consequences that are analyzed include non-noble gas activity released to the environment; number of early fatalities; and number of latent cancers.

Table 2 Contributions to Offsite Consequence by Nuclide for an SGTR Scenario

Element	Relative Contribution to Conditional Consequence (%)		
	Non-Noble Gas Activity	Early Fatalities	Latent Cancer Fatalities
Americium (Am)	0.0001	0	0.01
Antimony (Sb)	0.4	0.02	0.03
Barium (Ba)	3.9	0.7	0.5
Cerium (Ce)	8.1	0.07	0.08
Cesium (Cs)	0.3	2.7	77.0
Cobalt (Co)	0.03	0	3.7
Curium (Cu)	0.03	0.2	0.4
Iodine (I)	8.5	55.6	2.5
Krypton (Kr)	0	2.3	0.1
Lanthanum (La)	5.3	0.3	0.008
Molybdenum (Mo)	3.4	2.9	0.3
Niobium (Nb)	3.00	8.9	5.9
Neodymium (Nd)	1.4	0.002	0.007
Neptunium (Np)	35.4	0.06	0.006
Plutonium (Pu)	0.1	0.002	0.1
Praseodymium (Pr)	3.1	0.04	0.01
Rhodium (Rh)	1.1	0	0.01
Rubidium (Rb)	0.001	0	0.0005
Ruthenium (Ru)	4.1	4.7	7.5
Strontium (Sr)	4.9	0.8	0.3
Technetium (Tc)	1.8	0	0.003
Tellurium (Te)	3.1	20.5	1.1
Xenon (Xe)	0	0	0.3
Yttrium (Y)	6.1	0.2	0.06
Zirconium (Zr)	5.9	0.1	0.06

It can be seen from the results that different consequence measures lead to very different profiles of the relative risk importance of each nuclide. In the case risk is measured by non-noble gas activity of release for the SGTR scenario (Table 1), nuclides of Neptunium are found to be the largest contributor at 35%, while 15 other nuclides each individually contribute amounts between about 1 and 8%. Early fatalities, in contrast, can be attributed mainly to Iodine (56%) and Tellurium (also decays to iodine) (20%), which are both only minor contributors to radiological release activity, whereas the relative number of early fatalities due to Neptunium is negligible. When the number of latent cancers is used as a risk measure, the dominant nuclides are those of Cesium (77%) and Ruthenium (8%), both of which are ranked low in the profiles of the other two consequence measures for this particular scenario, and neither Neptunium nor Iodine are found to be prominent.

Comparison of Tables 2 and 3 also reveals that the relative importance of different nuclides is highly sensitive to the release mode even when employing the same consequence measure. In the case of non-noble gas release activity for the filtered venting scenario, Neptunium remains dominant although the distribution among all other elements is changed. Iodine (43%) and Krypton (54%) together are the dominant elements in contributing to early fatalities for the venting scenario, while Xenon results in 93% of the latent cancers. In contrast, note that the release activity consequence measure by definition

excludes the noble gases from any contribution to risk. In addition, it should be emphasized that these tables present two examples of releases from the core under non-oxidizing conditions; in postulated severe accidents that occur during shutdown, oxidizing conditions may result in larger releases of nuclides such as Ruthenium and therefore different relative risk contributions.

Table 3 Contributions to Offsite Consequence by Nuclide for a Filtered Venting Scenario

Element	Relative Contribution to Conditional Consequence (%)		
	Non-Noble Gas Activity	Early Fatalities	Latent Cancer Fatalities
Americium (Am)	0.0001	0	0.0001
Antimony (Sb)	0.2	0.001	0.002
Barium (Ba)	4.6	0.006	0.004
Cerium (Ce)	9.6	0.002	0.002
Cesium (Cs)	0.4	0.08	2.2
Cobalt (Co)	0.04	0	0.10
Curium (Cu)	0.04	0.001	0.002
Iodine (I)	5.7	43.5	1.8
Krypton (Kr)	0	53.9	2.9
Lanthanum (La)	3.6	0.001	0
Molybdenum (Mo)	3.8	0.07	0.01
Niobium (Nb)	4.0	0.3	0.2
Neodymium (Nd)	1.8	0	0
Neptunium (Np)	38.7	0.001	0.0001
Plutonium (Pu)	0.1	0.0001	0.003
Praseodymium (Pr)	4.0	0.0003	0.0001
Rhodium (Rh)	1.1	0	0
Rubidium (Rb)	0.001	0	0
Ruthenium (Ru)	4.3	0.02	0.03
Strontium (Sr)	3.7	0.004	0.001
Technetium (Tc)	0.4	0	0
Tellurium (Te)	3.5	2.2	0.1
Xenon (Xe)	0	0	92.7
Yttrium (Y)	4.5	0.001	0.0002
Zirconium (Zr)	6.1	0.001	0.001

3.2 Relative Contributions to Total Risk

The total plant risk using a particular measure of consequence can be defined as a frequency-weighted sum of conditional consequence components from each nuclide, each release category, and each individual sequence within those release categories using Equation (2) that can be written as

$$\text{Total plant risk} = \sum_{m} \sum_{j \in m} \sum_{k} f_j c_{jk} \tag{6}$$

Here m is the index of each release category $j \in m$ denotes the index of each individual Level-2 PSA sequence within release category m, f_j is the frequency (per year) of sequence j, and c_{jk} is the conditional consequence according to Equation (4). Therefore, one can define the relative risk contribution of an individual release category (i.e., class of Level-2 PSA sequences related by similar release characteristics) as:

$$\text{Relative risk contribution from release category } n = \frac{\sum_{j \in n} \sum_{k} f_j c_{jk}}{\sum_{m} \sum_{j \in m} \sum_{k} f_j c_{jk}} . \tag{7}$$

Using Equation (7), the total risk for the reference plant and the selected set of consequence weighting factors was calculated to be 1.5 x 10^{11} Bq/year of non-noble gas radiological activity. The total risk of radiological release as measured by early fatalities was calculated to be ~1 x 10^{-6} fatalities per year, while the total risk of latent cancers was found to be ~6 x 10^{-5} per year. Figure 1 shows the relative contribution to total plant risk by each release category for each of the three consequence measures.

As calculated by Equation (7) and illustrated in Figure 1(a), approximately 44% of total plant risk of non-noble gas radiological activity of release was found to derive from SGTRs below water, while other significant contributors included unfiltered containment venting (16%), LOCAs outside containment (14%), and containment isolation failures (11%). The corresponding breakdown for early fatalities (Figure 1(b)) was nearly identical to that for activity of release, with SGTRs below water accounting for 48% of the offsite consequences, unfiltered venting 11%, LOCAs outside containment 14%, and containment isolation failures 10%. Risk contributions as measured by latent cancer fatalities (Figure 1(c)) showed some modest differences, with SGTRs below water decreasing to 37% of total consequences, unfiltered venting 4%, LOCAs outside containment 6%, and containment isolation failures 10%. Filtered venting becomes a significant contributor to latent cancers at 38% due to their high frequency and large magnitude of Xenon release, for which a small but non-zero risk weighting had been used consistent with Reference [3]. Nonetheless, the other release categories dominant in the activity risk profile remain highly ranked in the latent cancer risk profile.

3.3 Large Release and Large Early Release Frequencies

A mean value for Large Early Release Frequency (LERF) may be calculated using several reasonable alternative definitions as to whether a particular sequence can be classified as a large early release according to the magnitude of its conditional consequence, including:

(a) Any releases that occur because of severe accidents that would entail an early containment failure (including containment isolation failure)

(b) Any releases that occur because of severe accidents that would entail early containment failure (including containment isolation failure) and containment bypass conditions

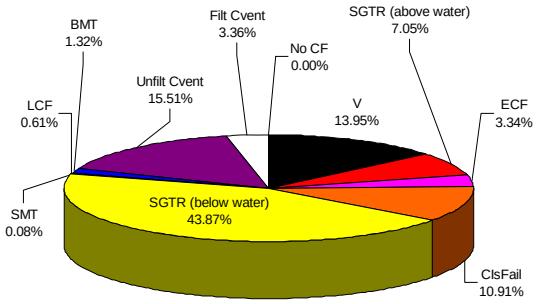
(c) Any release that would exceed specific thresholds in terms of fractional releases and timing of release (e.g., Cesium mass released to the environment within 10 hours equals or exceeds 1% of total core inventory);

(d) Any releases that occur because of severe accidents that would entail 10% or more of the initial core inventory of iodine;

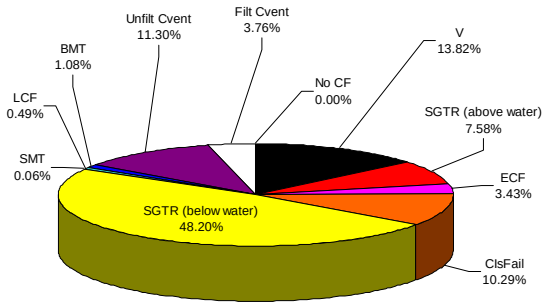
(e) Any releases that would exceed specific thresholds in terms of the activity associated with the release from the containment (e.g., Iodine-131 activity released to the environment within 10 hours equals or exceeds 2 x 10^{15} Bq (Swiss regulatory definition from Reference [3]); or

(f) A collection of all releases that would result in one or more early fatalities offsite [4].

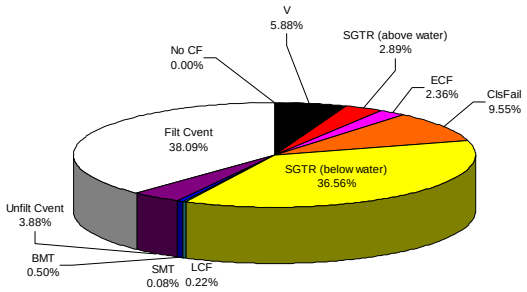
Table 4 shows the value of LERF as calculated using the Level-2 PSA model for the reference plant using definitions "c", "e", and "f" above for large early release (i.e., summing the frequencies of only those sequences which satisfy the relevant large early release criterion). Weighting factors as discussed in Section 2 were used in order to estimate early fatalities from the conditional release activities. It can be seen that all three definitions lead to very similar values for LERF of approximately 6 to 9 x 10^{-8} per year for the reference PWR. The differences between these alternative measures of LERF are negligible, and less than the magnitude of uncertainty associated with many PSA model inputs which led to these results. Since the results in Section 3.2 have shown that various measures of risk (especially for early consequences) correspond closely to one another, it is not surprising that they can serve as equivalent definitions of large early release for an appropriately established threshold value.



(a) Non-Noble Gas Activity of Release



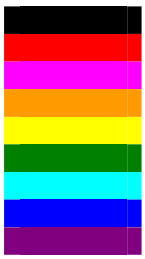
(b) Early Fatalities



(c) Latent Cancer Fatalities

Figure 1 Relative Contributions to Total Plant Risk by Release Category

Key:



LOCA Outside Containment (excluding SGTR)
SGTR Above Water
Early Containment Rupture
Containment Isolation Failure
SGTR Below Water
Sump Line Melt-Through
Late Containment Rupture
Basemat Melt-Through
Unfiltered Containment Venting
Filtered Containment Venting

Table 4 Large Early Release Frequency (LERF) by Various Measures

Criterion for Large Early Release	**LERF (per year)**
10-h Cesium release fraction ≥ 1%	9×10^{-8}
10-h ^{131}I release activity ≥ 2×10^{15} Bq	6×10^{-8}
Early fatalities ≥ 1	9×10^{-8}

Similarly, possible definitions of a large release for purposes of calculating Large Release Frequency (LRF) include:

(a) Cesium mass released to the environment for 48 hours following the accident equals or exceeds 1% of total core inventory;

(b) Total Cesium-137 activity released to the environment equals or exceeds 2 x 10^{14} Bq (Swiss regulatory definition from Reference [3]); and

(c) Total core damage frequency multiplied by the conditional probability of containment failure (including bypasses, failures of containment isolation, and other unfiltered release modes).

Table 5 shows the LRF value calculated for the reference plant using each of the criteria proposed above for a large release. As with the case of LERF, it can be seen that all three LRF measures functionally yield similar results within about a factor of three, rendering the different large release definitions functionally equivalent relative to the uncertainties involved in the PSA.

Table 5 Large Release Frequency (LRF) by Various Measures

Criterion for Large Release	LRF (per year)
48-h Cesium release fraction ≥ 1%	1 x 10^{-7}
Total ^{137}Cs release activity ≥ 2 x 10^{14} Bq	1 x 10^{-7}
Containment failure frequency	3 x 10^{-7}

4. Summary and Conclusions

Level-2 PSA calculations were made to determine the risk for a reference PWR as measured both by the non-noble gas radiological activity of release, and more directly in terms of traditional offsite health consequence measures (i.e., prompt fatalities and latent cancers). Use of these alternative definitions of risk results in somewhat different profiles as to which individual radionuclides are the most risk-significant. However, notwithstanding this observation, it is found that they all lead to very similar profiles of the total plant risk, and – with appropriately defined thresholds – they also can be used in establishing equivalent definitions of large release and large early release. These findings support the view that non-noble gas radiological activity of release – which can be calculated in a very simple and straightforward fashion from accident source terms, without resort to more complex computer codes or methods for modeling of radionuclide dispersion, transport, deposition, and induced health effects – serves as a satisfactory method of reporting severe accident risk, and can be used for various Level-2 PSA applications, including, identification of strengths, vulnerabilities, and risk-beneficial plant improvements.

5. References

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