Progress in NUCLEAR SCIENCE and TECHNOLOGY, Vol. 1, p.440-443 (2011)

ARTICLE

Comparison of Nuclear Power Plant Risk using Dose-based Risk Measure

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In the current risk-informed framework, core damage frequency (CDF) and large early release frequency (LERF) are being widely used as two representative alternative measures to a plant risk. As both measures are focused on frequency itself rather than the plant risk, a simplified and more risk-relevant measure (SiRD*)* based on both the frequency and the individual dose is proposed as a surrogate for CDF and/or LERF. The whole-body dose and thyroid dose at the exclusion area boundary are introduced to define the surrogate plant risk measure. The site atmospheric dispersion factor, the dose conversion factor for the semi-infinite cloud model for fission products, the breathing rate, and the total activity of the fission product are considered for the dose calculations. The SiRD indices have been calculated for the source term release categories that have been defined at UCN 3&4 (PWR) and WS 1 (PHWR) probabilistic safety assessments (PSAs) in Korea and they were used to compare the nuclear power plant risk as a relative risk measure. The results show that the individual risk at WS 1 is less than that at UCN 3&4, due to the lower release fraction of fission products and the lower frequency of the initiating events.

KEYWORDS: dose-based risk measure, nuclear power plant risk, whole-body dose, thyroid dose, SiRD

I. Introduction

In the current risk-informed framework[1-2], core damage frequency (CDF) and large early release frequency (LERF) are being widely used as two representative alternative measures to a plant risk. While the CDF criterion is presently considered as based on defense-in-depth, the LERF addresses public safety that is achieved for a given release and time, in some cases taking into account emergency measures (such as evacuation). As CDF and LERF are focused on frequency only, however, they are not sufficient to assess the plant risk, since the risk is defined by the multiplication of the frequency and the consequence.

There are other risk measures, such as containment failure frequency and the amount of fission products (Cs or I) released to the environment derived from the Level 2 PSA, and the doses to the public and early (or late) fatalities derived from the Level 3 PSA[3-4]. However, their use is limited due to the complexity and uncertainty in the post-core melt physical process during the severe nuclear accident progressions[5-6]. Along with the recent PSA technology improvement, by the way, the PSA results like containment failure frequency and the source terms are generally accepted as references for the decision-making processes[7], though there are still discussions on a PSA quality[8]. In this paper, we propose a simplified and more risk-relevant measure, SiRD (Simplified Risk measure based on Dose), taking into account both the frequency and the dose. SiRD fully uses the Level 2 PSA results in terms of the source terms and release frequencies. In addition, the individual dose from the released fission products is also considered to include the health effect, which is partially a part of Level 3 PSA. That is, SiRD integrates the PSA results to estimate the plant risk, but in a simple way. Then the SiRD indices calculated for the nuclear power plants can be used as a reference measure to compare the risk among the plants.

II. Formulation of Dose-based Risk Measure

Among many parameters representing the consequence from nuclear accidents, the dose at EAB is considered to define the proposed risk measure, SiRD. In addition, for the simple formulation, only the whole-body dose and the thyroid dose are taken into account at present.

1. Whole-body and thyroid dose calculation

The following assumptions are used for the whole body dose due to immersion in a cloud of radioactivity and for the thyroid dose due to inhalation of radioiodine[9]:

- All radioactivity releases are treated as ground-level releases;
- The dose receptor is a standard man;
- No credit is taken for cloud depletion by ground deposition and radioactive decay during transportation to the exclusion area boundary (EAB).

Then, the whole-body dose due to gamma radiation for a given time period is given as follows:

$$D_{WB} = \varphi \sum_j \{K_{WB}(j) \times Q(j)\} \quad (1)$$

Here, D_{WB} is the whole-body dose in mSv, φ is the site atmospheric dispersion factor during the time period in sec/m^3, $K_{WB}(j)$ is the whole-body dose conversion factor for the semi-infinite cloud model for fission product j in mSv-m^3/TBq-sec, and $Q(j)$ is the total activity of j released during the time period in TBq.

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The thyroid dose to an offsite receptor for a given time period is obtained from the following expression:

$$D_{TH} = \varphi \times BR \times \sum_{j} \{K_{TH}(j) \times Q(j)\} \qquad (2)$$

Here, D_{TH} is the thyroid inhalation dose in mSv, BR is the breathing rate during the time period in m^3/sec and $K_{TH}(j)$ is the thyroid dose conversion factor for fission product *j* in mSv/TBq-inhaled. The atmospheric dispersion factors, dose conversion factors and breathing rates required for computing doses are adopted from the typical models used to evaluate the environmental consequences of accidents [9].

2. Definition of SiRD

A risk index for the i^{th} accident sequence, $SiRD_i$ in mSv/yr, is defined as the frequency of an initiating event *i* multiplied by the dose from the released radioactive isotope *j*:

$$\begin{aligned} SiRD_i &= F(i) \cdot \sum_{j}^{FPs} \sum_{k}^{WB/TH} dose(i,j,k) \\ &= F(i) \cdot \varphi \sum_{j}^{FPs} \{Q(i,j) \cdot K_{WB}(j) + Q(i,j) \cdot K_{TH}(j) \cdot BR\} \end{aligned} \qquad (3)$$

Here, *F(i)* is the frequency of the i^{th} core damage sequence and *Q(i,j)* is the total activity of isotope *j* released from the i^{th} sequence. Then SiRD can be expressed by a sum of $SiRD_i$ for the i^{th} core damage sequence. When the modes of early and late containment failure (ECF and LCF) are concerned (both failure modes are closely related to the accident consequence), SiRD can be grouped as follows:

$$\begin{aligned} SiRD &= SiRD_{ECF} + SiRD_{LCF} \\ &= \sum_{i_1}^{ECF\ sequences} SiRD_{i_1} + \sum_{i_2}^{LCF\ sequences} SiRD_{i_2} \end{aligned} \qquad (4)$$

III. Plant Risk Evaluation

The fission products or radioisotopes used to calculate the whole-body and thyroid doses include Xe, I, Cs, Te, Ru, La, Zr, Nb, and Ce, which are considered in the MACCS2 computer code[10]. As the fission product groups defined in MACCS2 are different from those used in the other severe accident analysis codes[11-12], the radioisotopes that affect the thyroid dose with a relatively long half-life are chosen as the representative isotopes. The amount of fission products released from the plant was obtained from the Level 2 PSA for the reference plants[13].

1. Plant Risk at UCN3&4

Based on the above formulation, the SiRD is assessed at the UCN3&4 units. Instead of the sequence-wise calculations, SiRD was obtained for the source term release categories (STCs) 1 to 19, which binned the core damage sequences according to their source term release characteristics. Among these definition of STCs, STCs 3, 4, 14, 16 and 19 lead to the early containment failure and STCs 6 to 13 the late containment failure.

As two representative cases, the SiRD numbers for STCs 19 and 6 were given in **Tables 1** and **2**, respectively, with the radioisotopes used for the dose calculation and the conversion factors for the calculation of whole-body dose in mSv-m^3/TBq-s and thyroid dose in mSv/TBq. STC 19 represents the containment bypass coupled with core damage sequences like the steam generator tube rupture (SGTR) accident, causing the large early release of fission products to the environment. This source term category led to the risk of 18.1mSv/yr, and most of the risk was found to come from I-131 and Te-132. In the meantime, the SiRD value for the STC 6, leading to the late containment failure, was assessed as 0.55mSv/yr. This is mainly due that the late containment failure occurs usually more than 24 hours after the onset of accident, and thus most of the fission products are trapped inside the containment.

Table 3 summarizes the SiRD risk for all source term categories. As shown in Table 3, the total risk is estimated as 22.6mSv/yr and STC 19 occupies 80% of the total risk. The second greatest contributor to the plant risk is STC 3, which also belongs to the accident sequences causing the early containment failure. Instead, the contribution from the late containment failure (STCs 6 and 8) is less than 4% in this case.

Table 1 SiRDs Estimated for STC 19 at UCN3&4

nuclide	Activity (TBq)	Conversion factor		SiRD (mSv/yr)	
		WB	TH	WB	TH
Xe-133	4.2e6	1.551	-	1.8e-3	-
I-131	3.0e5	16.67	2.9e8	1.4e-3	8.5
Cs-137	3.8e5	25.26	7.9e6	2.7e-3	0.29
Te-132	1.8e6	-	5.3e7	-	9.3
Ru-106	1.2e5	-	1.7e6	-	~0
La-140	7.6e2	107.1	-	~0	-
Zr-95	5.9e2	33.0	-	~0	-
Nb-95	5.9e2	34.5	-	~0	-
Ce-143	7.1e3	11.69	-	~0	-
sum				5.9e-3	18.1

Table 2 SiRDs Estimated for STC 6 at UCN3&4

nuclide	Activity (TBq)	Conversion factor		SiRD (mSv/yr)	
		WB	TH	WB	TH
Xe-133	4.2e6	1.551	-	2.2e-3	-
I-131	5.6e3	16.67	2.9e8	3.1e-5	0.19
Cs-137	5.2e3	25.26	7.9e6	4.4e-5	0.0048
Te-132	5.9e4	-	5.3e7	-	0.36
Ru-106	2.7e3	-	1.7e6	-	~0
sum				2.2e-3	0.55

Table 3 SiRDs Estimated for the Important STCs at UCN3&4

STC	Freq. (1/yr)	Xe-133 (TBq)	I-131 (TBq)	Cs-137 (TBq)	Te-132 (TBq)	SiRD
3	1.71e-7	4.2e6 (95%)	3.0e5 (13%)	3.8e5 (13%)	1.8e6 (49%)	2.1
4	5.39e-8	4.4e6	7.0e4	1.1e5	3.7e5	0.15
6	1.71e-6	4.2e6	5.6e3	5.2e3	5.9e4	0.55
8	1.60e-6	4.2e6	4.1e3	6.7e3	9.3e3	0.19
14	3.22e-8	4.2e6	2.2e6	2.8e6	5.2e5	1.5
19	1.43e-6	4.2e6	3.0e5	3.8e5	1.8e6	18.1
sum						22.6

2. Plant Risk at WS1

Analyses similar to the case of UCN3&4 plants were done for the WS1 plant using the WS1-specific site dispersion factor. Among the 9 source term release groups, only STCs 6, 7, 8 and 9 are shown in **Table 4**, since the risks from other categories are negligible. As shown in Table 4, the total risk was estimated as 1.2mSv/yr and STCs 8 and 9, leading to the containment bypass sequences (SGTRs), occupy about 75% of the total risk. Though STC 7 represents the containment isolation failure causing the early containment failure, its risk is just 0.12mSv/yr due to the relatively low frequency of the initiating events. The risk from STC 6 with higher frequency is also not dominant as most of the fission products are contained in the containment when the very late containment failure occurs.

Table 4 SiRDs Estimated for the Important STCs at WS1

STC	Freq. (1/yr)	Xe-133 (TBq)	I-131 (TBq)	Cs-137 (TBq)	Te-132 (TBq)	SiRD (mSv/yr)
6	3.0e-7	4.1e6 (71%)	2.3e4 (0.75%)	1.9e3 (0.7%)	1.6e4 (0.33%)	0.17
7	3.6e-8	4.6e6	1.5e5	1.3e4	1.5e4	0.12
8	6.9e-7	5.5e6 (96%)	3.6e4 (1.2%)	3.3e3 (1.3%)	2.0e4 (0.42%)	0.55
9	1.1e-7	2.6e6	1.5e5	1.3e4	1.7e4	0.35
sum						1.2

IV. Discussion

In this study, the individual risk of SiRD based on the whole-body and the thyroid doses at UCN3&4 has been calculated to be 22.6mSv/yr. Among 19 source term categories, STC 19 has been assessed as the most dominant one. As this release category represents the early containment failure, a large release of fission products was obtained (about 13% of I and 49% of Te are released from the initial inventories). Also the relatively high frequency of the initiating event (1.43×10^{-6}/yr) contributes its high risk. In that case, it is worthy to mention that STC 19 occupies about 80% of the total risk in spite of its 2% contribution to the CDF[13)].

In the meantime, the total risk at WS1 was 1.2mSv/yr and STCs 8 and 9 have been found to be the major contributors occupying 75% of the total risk. Like UCN3&4 plants, these release categories also represent the SGTR sequences. In both plants, therefore, it will be the first step to reduce the frequency of the SGTR and to develop the severe accident management strategy to control the fission product release to the environment, from the viewpoint of risk management.

The individual risk at WS1 plant has been assessed as about 1/20 of the risk at UCN3&4 with the similar site dispersion factor. In the case of WS1 plant, it is expected that the relatively low release fraction of fission products and the low frequency of SGTR initiating events at WS1 play an important role for the low risk. At both plants, the thyroid dose is the main risk factor compared to the whole-body dose. Though SiRD has limitations to estimate the overall plant risk yet, this risk measure could be useful to compare the plant risk as long as it is applied to each plant in a consistent way.

VI. Conclusion

While the currently available CDF and LERF are focused on frequency only, the proposed risk measure SiRD provides a more integrated risk effect as it combines the frequency and the dose together. Its additional advantage is that it can be calculated from Level 2 PSA results by considering a dose for the consequence without performing the complicated Level 3 PSA. According to the present comparison for both plants, the plant risk at WS1 is less than that at UCN3&4 due to the lower release fraction of fission products and the lower frequency of the initiating events. The newly suggested SiRD can be a useful relative risk measure when comparing the plant risk or ranking the core damage sequences in the plant. As the steam generator tube ruptures are found to be the major risky initiating events at both plants, these initiating events should be managed by the appropriate operator actions and/or the plant improvement in order to protect the public from the accident.

Acknowledgment

This work has been carried out under the Nuclear R&D Program by the Ministry of Education, Science and Technology, Republic of Korea.

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