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A Study of New Risk Metrics for Non-Light Water Small Modular Reactor

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Since it is not suitable to use risk metric such as core damage frequency, for non-light water small modular reactors, other risk metrics are necessary to show the effects of safety improvement. Several risk metrics are suggested, and their usefulness is discussed by an illustrative example, in which the safety improvement by choosing a longer emergency planning zone is represented by the new risk metrics.

Keywords: risk metrics, non-light water reactor, emergency planning zone, small modular reactor

1. Introduction

For the light-water reactor (LWR), core damage frequency (CDF) and large early release frequency (LERF) are the risk metrics which show the safety level of the nuclear power plants (NPPs). However, non-light water (LW) small modular reactors (SMRs), such as molten salt reactors (MSRs), do not have risk metrics such as CDF or LERF due to the inappropriateness of the core melt concept.

Therefore, for non-LW SMRs, instead of considering risk metrics such as CDF and LERF, one of the new licensing requirements in design is to meet the frequency consequence (F-C) target as shown in Fig. 1 (NEI (2019) & NRC (2020)).

However, in many cases it is inconvenient not to be able to use simple risk measures, although it is a good idea to use the F-C curve in design. For example, it is difficult to demonstrate how much the safety of an NPP is improved by a design change or equipment upgrade. In particular, if we choose a longer distance of the Emergency Planning Zone (EPZ), it is not easy to show how much the safety (i.e. the off-site radiological risk) of the non-LW SMR is improved, since the results are mainly expressed in terms of the F-C curve instead of the risk metrics.

In fact, NEI 18-04 (NEI (2019)) only mentions a risk metric for non-LW SMRs with "integrated risks" without an example, as shown below;

> *integrated risks … calculated by summing the product of the frequency and consequence of each licensing basis event (LBE) over the full set of LBEs.*

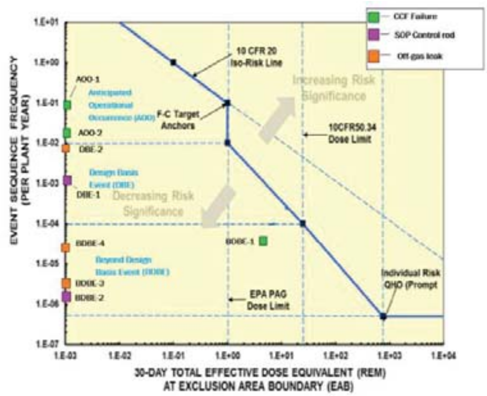

Fig. 1. F-C target and several licensing basis events example

Also, NEI 18-04 shows how to derive the 'risk significant LBEs' as follows;

> *Risk-significant LBEs are those with frequencies within 1% of the F-C Target with site boundary doses* (see crosshatched region of Fig. 2*).*

This paper proposes new simple risk metrics that can be derived from the F-C curve for non-LW SMRs. Using two different EPZs as an illustrative example, the 'integrated risks' of NEI 18-04 is explained in detail and the effectiveness of the proposed new risk metrics is described and compared with the NEI 18-04 risk metrics.

2. Risk Metrics of F-C Curve

The proposing risk metrics comes from the F-C curve which may be submitted for a design approval.

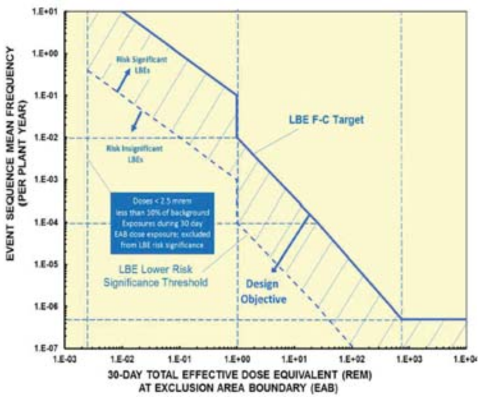

Fig. 2. Use of the F-C target to define risk-significant LBEs

The following new risk metrics for non-LW SMR are proposed.

- *Risk of Event Sequences (RES)* $= \sum_i^n (f_i * C_i)$
- *Average SM of ES (ASM)* $= (\sum_i^n SM_i)$ / n
- *No.of ES in Narrow SM(#NSM)*$=\sum_i^n NSM_i$
- *Minimum SM of ES (MSM)* $= \min SM_i$

where,

i = the event sequence (ES) i,
f_i = the frequency of ES i
C_i = the consequence of ES i
n = the total number of ES
SM = Safety Margin
= the distance from point (f_i, C_i) to F-C target (limit)
NSM = Narrow Safety Margin

3. Examples of Use of Risk Metrics

The following illustrative example can be used to check the usefulness of the proposed risk metrics.

3.1 *EPZ by US criteria*

In the US criteria, NUREG-0396 (NRC 1978) is still used for EPZ determination, and for the SMR EPZ case, RG. 1.242 (NRC 2021) was issued to accept scalable EPZ and aggregation of the accident sequence frequencies.

For non-LW SMR, EPZ distance is important since it is usually equal to exclusion area boundary (EAB) which is site boundary, and affects the off-site radiological consequences.

As an illustrative example, let's assume the following consequences and frequencies vary with different EPZ distances as shown in Table 1.

The longer EPZ distance for a non-LW SMR makes it easier to meet the F-C target since off-site consequences are calculated at the longer EPZ (= EAB). Now, we want to know how much the safety of the non-LW SMR can be improved by selecting 2 km EPZ instead of 1 km one.

Table 1. Frequency and consequence with two different EPZ distances

ES	Consequence at EAB (rem)		Frequency
	EPZ 1 km Case	EPZ 2 km Case	
1	1	0.2	1.01E-05
2	10	1	2.38E-06
3	50	10	1.20E-06
4	450	200	7.63E-07

Fig. 3 is the F-C curve of the illustrative example. In Fig. 3, red points and green points show the off-site consequences calculated at 1 km and 2 km EPZ for 4 event sequences (ESs), respectively.

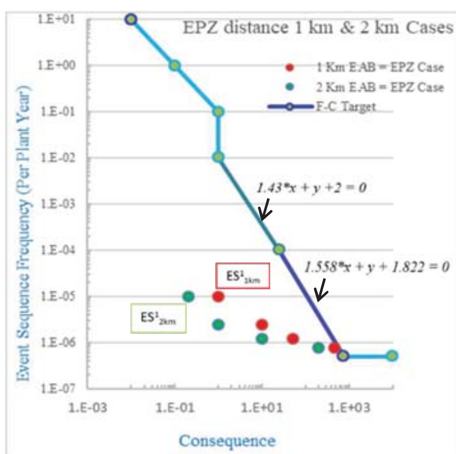

Fig. 3. F-C curves with different EPZ distances

In Fig. 3, red point ES^1_{1km} means event sequence 1 when EPZ distance is 1 km. Green point ES^1_{2km} means event sequence 1 when EPZ distance is 2 km.

In Fig. 3, it is easy to understand qualitatively that green points meet the F-C target with a larger safety margin.

In the next subsection, we will discuss the safety margin quantitatively using risk metrics.

3.1-1. *Risk of Event Sequence (RES)*

RES, one of risk metrics proposed in section 2, is equal to 'integrated risks' of NEI 18-04.

- *RES (EPZ 1 km)* $= \sum_1^4 (f_i * C_i)$
  *= (1.01E-05 * 1) + (2.38E-06 * 10) +…*
  = 4.37E-04 *(rem/yr)*

- *RES (EPZ 2 km)* $= \sum_1^4 (f_i * C_i)$
  *= (1.01E-05 * 0.2) + (2.38E-06 * 1)+…*
  = 1.69E-04 *(rem/yr)*

Comparing the RES of the 1 km case with that of the 2 km EPZ case, we can say quantitatively that the RES of the 1 km EPZ case is more than twice as high as that of the 2 km EPZ case. In other words, if we change the EPZ or EAB from 1 km to 2 km, the risk (RES) of the non-LW SMR reduces from 4.37E-04 to 1.69E-04 *(rem/yr).*

3.1-2. *Safety Margin (SM)*

In Fig. 3, the target line (green line) between 1E-02 and 1E-04 frequency can be expressed as below;

$$1.43*x + y + 2 = 0 \qquad (1)$$

where, x and y are the consequence and frequency with logarithmic scaling, respectively.

The blue line between 1E-04 and 5E-07 frequency can be expressed as below;

$$1.558*x + y + 1.822 = 0 \qquad (2)$$

where, x and y are the consequence and frequency with logarithmic scaling, respectively.

Since the shortest distance d between point (x_1, y_1) and the line

$$ax + by + c = 0$$

can be derived as follows:

$$d = \frac{|ax_1 + by_1 + c\,|}{\sqrt{a^2+b^2}}$$

The shortest distance d can be considered as the safety margin (SM), since the closer the ES points are to the F-C target line, the less safe the design is. For example, in Fig. 3, the safety margin for point ES^1_{1km} (= SM^1_{1km}) is the shortest distance from the point *(1, 1.01E-5)* to the line of Eq.(2) when EPZ = 1 km, and can be derived as follows;

$$SM^1_{1km} = d^1_{1km} = \frac{|ax_1 + by_1 + c\,|}{\sqrt{a^2+b^2}}$$
$$= \frac{|1.558x_1 + 1*y_1 + 1.822\,|}{\sqrt{1.558^2+1^2}}$$
$$= \frac{|1.558(log1) + 1*\log(1.01\mathrm{E}-05) + 1.822\,|}{\sqrt{1.558^2+1^2}}$$
$$= 1.7143\ (rem/yr)$$

Similarly,

$$SM^2_{1km} = d^2_{1km} = \frac{|ax_2 + by_2 + c\,|}{\sqrt{a^2+b^2}}$$
$$= \frac{|1.558x_2 + 1*y_2 + 1.822\,|}{\sqrt{1.558^2+1^2}}$$
$$= \frac{|1.558(log10) + 1*\log(2.38\mathrm{E}-06) + 1.822\,|}{\sqrt{1.558^2+1^2}}$$
$$= 1.2118\ (rem/yr)$$

Thus, after deriving SM^3_{1km}, SM^4_{1km} using Eq.(2),

- *Average SM of ES (when EPZ 1 km, n=4)*
  $= (ASM)_{1\ km}$
  $= (\sum_i^n SM_i)$ / n
  = (1.7143+1.2118+0.7842+ 0.0874)/4
  = 0.95 *(rem/yr)*

- *Average SM of ES (when EPZ 2 km, n=4)*
  $= (ASM)_{2\ km}$
  $= (\sum_i^n SM_i)$ / n
  = (2.3025+ 2.0534+ 1.3724+ 0.3838)/4
  ≅ *1.53 (rem/yr)*

Therefore, if we change the EPZ or EAB from 1 km to 2 km, the ASM increases from *0.95* to *1.53 (rem/yr),* which means a safer design.

3.1-3. *Risk significant LBEs*

As mentioned in section '1. Introduction', according to NEI 18-04 it is a risk significant LBE if the ES point is located within the crosshatched area of Fig. 2 which is within 1% of the F-C target with site boundary doses.

Let's assume that the crosshatched region is between blue and yellow line in Fig 4. Thus, if an ES locates between the yellow and blue line in Fig 4, the ES is a risk significant LBE.

Counting the ES points located in the crosshatched region in Fig. 4, two ESs (i.e. ES^3_{1km} and ES^4_{1km}) belong to risk significant LBEs when the EPZ distance is 1 km. When the EPZ distance is 2 km, only one ES (i.e. ES^4_{2km}) belongs to the risk significant LBE.

The safety margins of ES^3_{1km}, ES^4_{1km} and ES^4_{2km}, i.e., SM^3_{1km}, SM^4_{1km}, and SM^4_{2km} are 0.7842, 0.0874, and 0.3838 *(rem/yr)*, respectively.

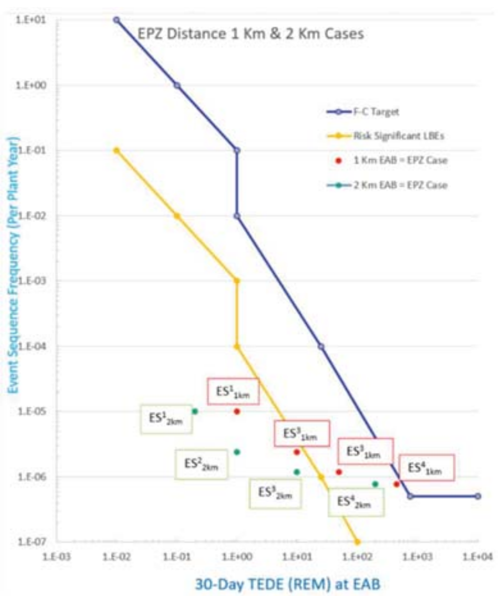

Fig. 4. ESs varied with different EPZ distances

In Fig. 4, the shortest distance between the blue and yellow parallel lines between frequency 5E-7 and 1E-4 is 1.08 *(rem/yr)*, which is the upper SM limit. All ESs with a SM of less than 1.08 *(rem/yr)* have a narrow safety margin (NSM), which means that the ESs are the risk significant LBEs, and thus, ES^3_{1km}, ES^4_{1km} and ES^4_{2km} have NSMs and are also the risk significant LBEs.

The advantage of using NSMs is that significant LBEs can be identified easily and quickly using a calculation algorithm without checking whether the ES's frequency is within 1% of the F-C Target through F-C curve graph. The number of NSM of 1 km EPZ and 2 km EPZ are 2 and 1 respectively. This means that the longer the EPZ distance, the greater the safety margin. Also, the minimum SM of ES (= MSM) is 0.0874 (rem/yr) of ES^4_{1km}. With the MSM, we can realize how much safety margin we have.

3.2 Multi-module effect

Non-LW SMR shall satisfies the F-C target as shown in Fig. 4 (NRC 2020, NEI 2019). Since expressing the frequency metric on a per plant year basis would reflect the number of accidents depending on the number of modules used, the more modules we use, the higher the frequency, which could be a critical disadvantage.

In the illustrative example of Fig. 4, if EPZ distance is 1 km, ES^4_{1km} satisfies F-C target by a narrow margin. However, if the non-LW SMR has two modules in a plant, the event sequence frequency of ES^4_{1km} becomes double in the plant (i.e., 7.63E-7 → 1.53E-6), and which cannot meet the blue line F-C target (<1E-6) in Fig. 4.

When EPZ distance is 2 km, if the non-LW SMR has five modules in a plant, the event sequence frequency of ES^4_{1km} is increased by as much as five times in the plant (i.e., 7.63E-7 → 3.82E-6), and which still meets the blue line F-C target (< 3.92E-6) in Fig. 4.

This means that if the EPZ distance is 1 km, only 1 module can be used. On the other hand, if the EPZ distance is 2 km, 5 modules can be used in the plant.

4. Conclusions

For non-LW SMR, several risk metrics are proposed. Although some of them are only mentioned in NEI 18-04, they are well explained with an illustrative example in this paper. The proposed new risk metrics are all easily and quickly calculated from the F-C curve, and are useful to show quantitatively how much the safety of the non-LW SMR is improved when the EPZ distance is changed.

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