A New Risk Metric to Consider the Environmental Risk Caused by Nuclear Accident

Hongchun DING[a,b,c], Yongfu WANG[d], Jiejuan TONG[a,b,c], Liguo ZHANG[a,b,c]

[a]Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing, 100084, China

[b]Collaborative Innovation Center of Advanced and Safety Nuclear Energy Technology, Tsinghua University, Beijing, 100084, China

[c]The Key Laboratory of Advanced Reactor Engineering and Safety of Ministry of Education, Beijing, 100084, China

[d]Huaneng Nuclear Power Development Co.Ltd, Beijing, 100031, China

dinghongchun2010@163.com; tongjj@tsinghua.edu.cn; lgzhang@tsinghua.edu.cn

Abstract: The three accidents, i.e. Three Mile Island Accident, Chernobyl Accident and Fukushima Daiichi Accident, are undeniable disasters in the history of nuclear industry. However, the actual accident impacts on public health were significantly inconsistent with their disastrous reputations. For example, thousands of people were killed due to the Fukushima tsunami, but no early radiation induced health effects were observed because of the nuclear power plant accident. From this point of view, the nuclear accidents still meet the existing quantitative safety objectives, i.e. the two 0.1% criteria defined by NRC Safety Goal Policy Statement. Many people offered criticism on the existing safety goal definition and there are strong needs to add the requirements on environmental and societal effects of nuclear accidents despite of the fatality effect.

This paper intends to propose a new risk metric that can be used to consider the environmental risk of nuclear accident. The proposed risk metric is defined as the frequency of exceeding the pre-defined set of environmental effect criteria (EEF). The Criteria of Limited Impact (CLI) proposed by the European Utility Requirement (EUR) are referenced as the environmental effect criteria in this paper. The Passive Pressurized Light Water Reactor (AP1000) is taken as the pilot study candidate to check the feasibility of the proposal. The feasibility analysis uses MELCOR accident consequence code system (MACCS) code as the computation tool. The paper will give out the EEF and summarize the key technical considerations during the assessment.

Key words: Environmental and Societal Risk Metric; Criteria of Limited Impact; AP1000; MACCS

I. Introduction

The existing quantitative safety objects (QHOs) are the two 0.1% criteria defined by NRC Safety Goal Policy Statement in 1986[1]. The QHOs were originally developed to provide guidance as to the level of "public protection which nuclear plant designers and operators should strive to achieve [2]". The QHOs are stated in terms of public health risk, with one QHO addressing individual risk and the other addressing societal risk [1]. In practice, the surrogate measures concerning the frequency of core damage frequency (CDF) and large early releases frequency (LERF) provided additional guidance regarding the safety goals.

The definitions of the QHOs are based on directly induced prompt fatalities and cancer fatalities by nuclear accidents, but these definitions are criticized for their inability to address the actual impact of severe nuclear accidents. Taking Three Mile Island Accident and Fukushima Daiichi Accident for example, there is no early radiation induced health effects were observed among workers and members of the public that could be attributed to the accidents. What's more, the estimation of radiation dose of the two above accidents indicated that the effective dose incurred by individual around the accident sites was low enough that no discernible increased incidence of radiation-related health effects are expected among exposed members of the public and their descendants [3, 4]. From this point of view, the nuclear accidents still meet the existing quantitative safety objectives, but they also lead to a great panic of public against nuclear power. In other words, the QHOs and their surrogate measures cannot explain the disastrous reputations of nuclear accidents and the concerning of safety goals for nuclear accidents need to be expanded to include the caused environmental and societal impacts of nuclear accidents.

The environmental and societal impacts due to the released radioactive material from accidental reactors did have great influence in terms of timescale and ground area. Taking Chernobyl Accident in 1986 for example, large amounts of lands in Europe were affected by the released radioactive material and more than 200 thousand square kilometers of lands contaminated by radioactive cesium. Due to the deposition of the radioactive materials released to the atmosphere, there were more than 100 thousand people evacuated that year, and more people in the adjacent area evacuated during the following next few years [5].

In conclude, the existing quantitative safety objectives, i.e. the two 0.1% criteria, which the definitions are based on directly induced prompt fatalities and cancer fatalities by nuclear accidents, could not characterized the environmental and societal effects caused by nuclear accidents very well. To some extent, there are strong needs to propose a new risk metric to measure the environmental and societal effects of nuclear accidents despite of the fatality effects. The new environmental risk metric, proposed in this paper, will focus on the exposures of the public and the contamination of ground.

This paper will give out the new environmental risk metric and summarize the key technical considerations during the assessment. The Passive Pressurized Light Water Reactor (AP1000) is taken as the pilot study candidate to check the feasibility of the proposal. The feasibility analysis uses MACCS code as the computation tool.

II. Proposal of New Risk Metric

The new environmental risk metric should be based on the existing quantitative safety targets and the general environmental risk assessment method at present. In this paper the Criteria for Limited Impact (CLI), which were set up by European Utility Requirements (EUR) in 1992 is selected as the pre-defined set of environmental effect criteria. The general environmental consequence analysis method, which assesses the dispersion and deposition of the released material and calculates the exposures of the public, is used to check the feasibility of the proposal [6].

1. The Criteria for Limited Impact

The Criteria for Limited Impact (CLI) are the quantitative safety targets set up for Design Extension Conditions by EUR, which was developed by major European power producers jointly. It involves the four following design targets [7]:

(1) No Emergency Protection Action beyond 800 m from the reactor;

(2) No Delayed Action at any time beyond about 3 km from the reactor;

(3) No Long Term Action at any distance beyond 800 m from the reactor;

(4) Limited economic impact out of the plant.

The (1) to (3) targets are in support of simplification of the emergency planning and off-site countermeasures. The fourth objective deals with limitation of the potential economic impacts of a severe accident. The first three targets of CLI shall be verified independently according to the following methodology:

(1) The releases from the plant to the atmosphere are broken down into the 9 reference isotope groups;

(2) These releases are combined and compared with one criterion according to the following formula:

$$\sum_{i=1}^{9} R_{ig} \cdot C_{ig} + \sum_{i=1}^{9} R_{ie} \cdot C_{ie} < criterion\,. \tag{2-1}$$

In the linear combination formula:

R_{ig} and R_{ie} are the total releases (at ground and elevated level) of the nine reference isotopes during the related release period from the containment system. EUR uses releases for these design targets instead of doses is to minimize the uncertainty caused by the discrepancies between dose calculation methodologies. C_{ig} and C_{ie} are the coefficients related to environmental effects of unitary releases. Although there is no detailed information could be found in the EUR for the values of coefficients in CLI, we could acknowledge that the coefficients in CLI concerning the general site features, for example atmospheric dispersion factor, dose conversion factor etc. [8].

R_{ig} and R_{ie} take each 3 different values according to the target to be verified. For target (1), $R_{(1)ig}$ and $R_{(1)ie}$ are the releases calculated during the first 24 hours and acceptance criterion is 0.05. For target (2), $R_{(2)ig}$ and $R_{(2)ie}$ are the releases calculated during the first 4 days and acceptance criterion is 0.03. For target (3), $R_{(3)ig}$ and $R_{(3)ie}$ are the releases caused by this severe accident and acceptance criterion is 0.1. Using the linear combination formula (2-1), one can quickly estimate the potential offsite consequence of released radioactive nuclides.

The CLI thresholds are set in order to limit the environmental and societal consequences resulting from effects on public health and contamination of soil and water for design basis conditions (DBCs) and design extension conditions (DECs). The target values given for releases are consistent with this objective and taking account of international standards such as ICRP 63 and the Basic Safety Standards. It is believed that, for most of the Core Damage sequences with appropriate behavior of the Containment System and for most of the Containment System Bypass sequences, the releases can be kept well within the given criteria [7].

2. Proposal of New Environmental Risk Metric

There are a number of limitations related to the current safety goals. These limitations include the inability of the QHOs and current subsidiary goals to take into account the difference effects caused by reactors of different sizes and to deal with multi-unit sites [9]. In addition to these, the QHOs and the subsidiary goals which based on the early prompt fatalities and cancer fatalities caused directly by released radioactive material could not reflect the environmental and societal risk, the affected time scale and ground area, of nuclear accidents. Therefore, this paper is trying to propose a new environmental and societal risk metric to address the effect to adjacent environment and society of the nuclear accidents. The proposal will have certain guidance in emergency response planning and public protections under severe nuclear accidents.

The new environmental and societal risk metric proposed in this paper, signed as EEF, is defined as the frequency of exceeding the pre-defined set of environmental effect criteria. CLI in this paper are chose as the pre-defined environmental effect criteria for its ability in delineating environmental risk and its validity verified in EUR documents. The new environmental risk metric-EEF should give the ability to evaluate the severity of the accidents as well as consider the frequencies of sequences to avoid unnecessary planning.

As for the severity of the accidents, it could be well addressed by the exceeding probabilities of the corresponding release categories above CLI targets thresholds for they express the conditional probabilities over specified dose thresholds under the accidents. The consideration for frequencies of accident sequences is consistent with the fact that severe nuclear accidents with large released materials will be expected only under extreme conditions. Thus to conclude, the new environmental risk metric-EEF is defined as the cumulative exceeding probabilities of all release categories beyond CLI targets thresholds with the corresponding occurrence frequencies as weighting factors. The formula is shown as following:

$$EEF = \sum_{1}^{n} f_i P_{i1} + \sum_{1}^{n} f_i P_{i2} + \sum_{1}^{n} f_i P_{i3} \,. \qquad \text{(2-2)}$$

In the linear formula (2-2), f_i is the occurrence frequency of release category i,

P_{i1}, P_{i2} and P_{i3} are the conditional probabilities of release category exceeding the corresponding targets thresholds of CLI, which could be calculated by MACCS code. Number n is the total release categories of a reactor obtained from its Level 2 PRA analysis. The unit of EEF is per reactor year.

The occurrence frequencies of release categories could be get from the source term analysis. The conditional probabilities of release categories exceeding the corresponding targets thresholds of CLI is shortly signed as exceeding probabilities in this paper. The calculation method for these exceeding probabilities is based on *Planning Basis for the Development of State and Local Government Radiological Emergency Response Plan in Support of Light Water Nuclear Power Plants* (NUREG-0396) [10], in which the CCDF curves express exact meaning of these exceeding probabilities.

The definition of EEF is similar to that of CDF/LERF in forms, which are both the cumulative products of frequencies and probabilities. As for CDF/LERF, the frequencies address the occurrence of initiating events; well the probabilities address the failure of safety related systems. So in contrast, the occurrence frequencies of release categories in EEF could be treated as the initiating event leading to large off-site releases and the exceeding probabilities in EEF measure the failure of release categories failed to meet the CLI targets. From this point of view, the proposal-EEF in this paper could be treated as the subsidiary goal for CLI.

Since the CLI thresholds estimate the environmental and societal consequences resulting from effects on public health and contamination of soil and water for DBCs and DECs [7], EEF thus could be seen as a more comprehensive metric to evaluate the integrated environmental and societal risk for a single reactor. There are two reasons support this announcement. The first reason is that EEF could take account of all the release categories of a reactor, therefore it could cover almost all known environmental and societal consequences might be caused by a plant. To put it another way, the first reason characterizes the spatial scale of accidents. The second reason is that EEF integrates all CLI targets into one, hence the time scale in EEF is beginning along with the accident and could last up to 50 years. .

In conclusion, the proposal EEF could be treated as the subsidiary goal of CLI. EEF takes account of all the environment consequences that a plant might be lead to the surrounding environment and long enough considering time after accidents. Therefore, EEF is able to evaluate the total environment risk of a plant.

III. Case Study - AP1000

The Westinghouse Advanced Passive PWR (AP1000) is one of the representations of the third generations. Massive passive features and extensive plant simplifications enhance the safety of AP1000. This paper chooses AP1000 as the case study candidate to check the feasibility of the new environmental risk metric and to see the environmental risk level of AP1000. The detailed information used in this paper could be found in Xudapu reactor power plant report[11] and Level 2 PRA report of AP1000[12].

1. Release Categories of AP1000

Seven release categories of beyond design basis accidents are given for AP1000 and the belief introductions to them are described as following:

- Intact Containment release category (IC): Containment keeps intact during the entire accident process. The radioactive material released to the atmosphere through the routine leakage.
- DIRECT release category: The modification of IC with conservative estimations.
- Containment Bypass release category (BP): The failure of containment occurs before the core damage. Fission products enter into the environment through the connections between reactor coolant system with secondary loop and other connection systems.
- Unisolated Containment release category (CI): The failure of containment occurs before the core damage. Fission products released out due to the failed close of penetration items or valves which connect containment with outside.
- Containment Early Failure release category (CFE): Fission products release to the failed containment is induced by the dynamic phenomenon, e.g. hydrogen burning, steam explosion and failure of pressure vessel, of severe accidents caused by core melting before core collapsing.
- Containment Intermediate Failure release category (CFI): Fission products release to the failed containment due to the dynamic phenomenon, e.g. hydrogen burning, steam explosion, of severe accidents caused by core melting less than 24 hours after core collapsing.
- Containment Late Failure release category (CFL): Fission products release to the failed containment is due to the dynamic phenomenon, e.g. failure of passive containment cooling system, of severe accidents caused by core melting more than 24 hours after core collapsing.

Six of them: IC, BP, CI, CFE, CFI, and CFL are studied in this paper both for checking the feasibility of new environmental risk metric and improving the understanding about beyond design basis accidents of AP1000.

2. The Feasibility of New Risk Metric

The occurrence frequency in EEF could be obtained from Level 2 PRA report of AP1000. The exceeding probabilities in EEF could be calculated by MACCS code. MACCS is a severe accident risk assessment code developed by Sandia National Laboratory (SNL) for United States Nuclear Regulatory Commission (NRC) [13]. MACCS models the offsite consequence of a severe reactor accident with segmented released plumes of radioactive material into the atmosphere. A MACCS calculation could estimate the range and probability of the health effects induced by radiation exposures that not avoided by protective actions due to this accident.

Here are some statements about the calculation for exceeding probabilities:

(1) The analysis for each release category is based on envelopment method, i.e. taking a representative source term to take place the whole release category.

(2) The calculation for each isotope group is also based on envelopment method,

i.e. selecting one representative nuclide to replace the whole isotope group, which agrees with CLI design targets and their independent verify methodology (2-1).

(3) For P_{i1} in EEF, the exceeding probabilities of each release category over the target 1 threshold of CLI, the settings in MACCS code are as following: the released time of radioactive material is within 24 hours after accident; the exposure duration is within the emergency phase (7 days). For P_{i2} in EEF, the corresponding settings in MACCS code is release for 4 days and the exposure duration is within 30 days after accident. For P_{i3} in EEF, the release time is the entire release duration of accident and the exposure time is 50 years. The exceeding probabilities calculated are shown in Table 3.1.

Table 3.1 Exceeding Probabilities of Each Release Categories

Release category	Exceeding Probabilities (%)		
	CLI Target 1	CLI Target 2	CLI Target 3
IC	0.00	1.00	0.00
BP	100	98.0	0.00
CI	100	100	0.00
CFE	91.0	99.0	0.00
CFI	54.0	100	0.00
CFL	100	99.0	0.00

The results in Table 3.1 indicate that during the emergency phase, the results below CLI Target 1, the exceeding probability of IC release category is the only one meets the target (1) threshold of CLI. In other words, the other five release categories will exceed the target (1) threshold of CLI with very high probabilities despite of the weather conditions. The situation during intermediate phase, the results below CLI Target 2, is similar to that of emergency phase. For the long-term phase, it is long enough for the radioactive material reduced to lower than target (3) threshold of CLI with the help of natural removal process e.g. radioactive decay and weathering.

According to the formula 2-2 and with the above information in Table 3.1, the new environmental risk metric-EEF calculated for AP1000 is 4.01E-8 per reactor year. This number-4.01E-8 per reactor year expresses that the total environment risk caused by an AP1000 plant in every single year is 4.01E-8.

3. Risk Dominant Nuclides of AP1000 Release Categories

The six release categories studied in this paper characterizes different release times, release mode and concerning time after accident. The risk dominant nuclides for offsite projected doses of these release categories will be a more intuitive and important way to understand how to do before, during and after the accident. With the knowledge that the sum of projected doses for individual nuclide is almost same with the projected dose of all nuclides affect together, the risk dominant nuclides for each release category can be obtained through MACCS code. Table 3.2 shows the final results of risk dominant nuclides for each release category in descending order with the last nuclide contributing about 10% to the total offsite projected dose.

Table 3.2 Risk Dominant Nuclides of Each Release Category

Accident phases	IC	BP	CI	CFE	CFI	CFL
Emergency Phase	Ba-140 I-131 Ru-103 Sr-90	I-131	I-131 Ba-140 Ru-103	I-131 Ru-103 Ba-140	Ba-140 Sr-90 Ru-103 La-140 I-131	La-140 Ba-140
Intermediate Phase	Cs-137 Sr-90 Ba-140	Cs-137	Cs-137 Sr-90	Cs-137	Sr-90 Cs-137	Sr-90 Ru-103 Ba-140
Long-term Phase	Cs-137 Sr-90 Ba-140	Ru-103 Sr-90 Ba-140 I-131	Ru-103 Ba-140 Sr-90 I-131	Sr-90 Ru-103 Ba-140 I-131	La-140 Ru-103 Ba-140 I-131 Cs-137	Sr-90 Cs-137 Ru-103 Ce-141

The results demonstrate that the well-acknowledged nuclide I-131 plays an important role in emergency phase of the accident; and for the intermediate and long-term phase, Cs-137 and Sr-90 are will accepted for their physical and chemical characteristics. In addition to this, Ba-140 and Ru-103, the low-volatile gamma emitting fission products, have a certain effect in all release categories except BP in emergency phase. As for intermediate and long-term phase, the low-volatile gamma emitting fission products such as Ba-140, Ru-103, La-140, Ce-141 do have vital influence in some release categories especially in CI, CFE and CFI.

The release portion of low-volatile elements are mainly due to the nature of the accident for they have not been detected at significant level in the area around the Fukushima Daiichi Nuclear Power Plant (NPP) [14] and this contracts with the releases from the Chernobyl NPP [5]. Because the release is mainly due to core overheating and fuel melting, without the presence of air, less volatile elements are therefore not released in the Fukushima Daiichi NPP. While the explosion at the Chernobyl NPP releasing fragments containing these less volatile elements. As for AP1000, the impression that large amount of low-volatile elements released given by calculation may not agree with the actual accident situation with the reason that there are lots conservative considerations and treatments during the estimation methodology and process of source terms analysis.

The knowledge of risk dominant nuclides can be useful both for normal operating stages and accident stages. For example, during the normal operating conditions, the plant designers can layout the removal mechanisms aimed at the risk dominant nuclides and project specific protective actions under accident conditions at the same time.

IV. Discussion and Conclusion

A new environmental risk metric, signed as EEF, is proposed in this paper with the purpose to quantitatively assess the potential environmental and societal risk caused by reactor accidents and as a complement of current existing safety criteria. The Criteria for Limited Impact (CLI) are set up as the pre-defined set of environmental effect criteria and used as the theoretical foundation for EEF. The proposal-EEF is defined as the cumulative exceeding probabilities of all release categories of a NPP beyond CLI targets with the corresponding occurrence frequencies as weighting factors. EEF evaluates the severity of the accidents as well as considers the frequencies of sequences to avoid unnecessary planning.

Compared with CDF/LERF, the proposal-EEF in this paper can be treated as the subsidiary goal for CLI to quantitatively evaluate the environmental and societal risk, public health effects and contamination of soil and water. Since CLI are set up for DBCs and DECs for next generations, e.g. the third and fourth generations, they could not suitable for assessing the environmental risk of majority operating reactors, which the designs are mainly belong to 2^{nd} or advanced 2^{nd} generations. The subsidiary goal EEF in contrast is more flexible and could be used to evaluate the environmental risk for all the reactors with different thresholds.

The pilot study of AP1000 checks the feasibility of EEF and gives the preliminary cognition of the magnitude of EEF. The interpretation of that number is insufficient for lacking comparison and it could be more clearly with lots case studies. The rational interval, which marks no significant effects to environment for EEF need to be confirmed further.

The proposal-EEF also illustrates the effort could be made to diminish the environmental risk by two auxiliary ways. Improving the designed safety features to completely eradicate or further decrease the frequencies of such accident sequences which will lead to large releases. And at the same time, setting up the removal mechanisms aimed at the risk dominant nuclides to lower the exposure to public and the contaminant into the ground.

V. Acknowledgement

The program is supported by Chinese national major projects funded projects (ZX069), national energy applied technology research and demonstration project (NY20111003-1) and technology project of China HUANENG Group headquarters.

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