Analysis of different quantitative safety goals for nuclear power plants

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Abstract:

As the multi-unit risks or site-level risks from nuclear power plants receive a lot of attention after Fukushima accident, the discussions on the safety goals for multiple units of nuclear power plants or a nuclear power plant site are gradually emerging. Safety goals are closely related to the results of probabilistic safety assessment (PSA), and different levels of PSA results are used for quantitative safety goals in different countries. Safety goals in the form of prompt and cancer fatality risks are set so that those from nuclear power generation should be less than those from other forms of risks in the society, and the results of Level 3 PSA are compared with such quantitative safety goals. Safety goals in the form of large release frequency (LRF) are set to prevent land contamination nearby nuclear power plants so that large-scale relocation of population can be avoided, and the results of Level 1 or 2 PSA are compared with such quantitative safety goals. When different quantitative safety goals are used together, it is evident that those safety goals need to be consistent to each other. This paper reviews these quantitative safety goals and confirms the relation among them.

Keywords: PSA, Quantitative safety goals, Prompt/Cancer fatality, LRF

1. INTRODUCTION

As the discussions on the multi-unit risks are emerging after Fukushima accident, interests in safety goals for multi-unit level or site level of nuclear power plants are increased. Most countries that have nuclear power plants are setting safety goals for risk from nuclear power plants. Safety goals for nuclear power plants are generally established as qualitative safety goals and quantitative safety goals. Qualitative safety goals are set to be easy for the public to understand. Nuclear safety goals generally include the statement that risks from nuclear power plants should not give any additional risks and should protect individuals, society, and the environment as qualitative safety goals. Then, for the answer how to achieve the qualitative safety goals, quantitative safety goals are established. There are several quantitative health objectives, which are established differently for each country. These quantitative safety objectives are closely related to the results of PSA and are also relevant among them. This paper reviews, compares and analyzes these quantitative safety goals to examine the consistencies among them.

2. Quantitative safety goals

There are various quantitative safety goals for each country to address the acceptable risks of nuclear power plants. For example, in the US, there are prompt and cancer fatality risks, core damage frequency(CDF), large early release frequency (LERF) for quantitative safety goals. In Canada, quantitative safety goals consist of the criteria for CDF, small release frequency(SRF), and large release frequency (LRF). In Japan, there are also quantitative health objectives for LRF, CDF, and Containment failure frequency(CFF). Annual dose is also established for quantitative safety goals in Finland. These quantitative safety goals in different countries summarize in Table 1.
In this paper, prompt and cancer fatality risks, LRF, CDF, and LERF are reviewed among quantitative safety criteria because these four quantitative criteria are established in Korea. Criterion for prompt and cancer fatality risks is one of the health objectives for nuclear power plants applied in US and Korea. In the US and Korea, it has been set that prompt and cancer fatalities from nuclear power plants should be less than 0.1% of the risks from other accidents or cancer. [1,2] In Japan, it was considered

that prompt and cancer fatality from nuclear power plants should not exceed the frequency of 1E-6 per year, respectively in interim report. [3]
Countries such as Canada, Finland, and Sweden establish the nuclear safety goals of LRF instead of prompt and cancer risks. The criterion generally limits the release of Cs137 100TBq when an accident occurs. This criterion is interpreted as 10^{-6} per year in Canada, as 5×10^{-7} per year in Finland, and 10^{-7} per year in Sweden. [3,4,5,6] Similarly, the criterion of large release of radioactive material was also considered to adopt for safety goals of nuclear power plants in the US. [1]
CDF and LERF are generally used to support the prompt and cancer risks. In Korea, CDF and LERF are set as target values corresponding to the prompt and cancer criteria. These criteria are respectively 10^{-4} per year and 10^{-5} per year for CDF and LERF. [7] Theses criteria are also considered as subsidiary criteria for prompt and cancer fatality in the US. In addition, CDF is mainly adopted for safety goals of nuclear power plants in many countries.

Table 1: Quantitative safety goals in different countries

Country	Safety Goals
United States	Qualitative (Individual/Societal), Quantitative (Prompt/Cancer, 0.1%) Subsidiary goals (CDF, LERF)
Canada	Qualitative (Individual/Societal), Quantitative (CDF, SRF, LRF)
Korea	Qualitative, Quantitative (Prompt/Cancer, 0.1% & LRF) Subsidiary goals (CDF, LERF)
Japan	Qualitative, Quantitative (Prompt/Cancer, 10^{-6} /ry, LRF) Performance goals (CDF, CFF)
Finland	Qualitative, Quantitative (Annual dose, Cs137) Probabilistic Design Objectives (CDF, LRF)
Sweden	Qualitative, Quantitative (Long-term ground contaminate, Short-term fatality) Subsidiary goal (LRF, 10^{-7} /yr)

2.1. Backgrounds

Prompt and cancer fatality risks are compared with other societal risks. These criteria are generally required to be less than 0.1% of other risks. The 0.1% ratio is based on comments and suggestion from public and industries in the US, considering public comments and workshops for developing safety goals of nuclear power plant. Many industry commenters at that time said that 1% is more appropriate than 0.1%, and 0.1% is high to achieve. [8] With two-year evaluation period, nuclear safety goals applying 0.1% ratio was published in the policy statement in 1986. At that time, the first phase of evaluation period was to gather useful information for the PSA study. [9]
In most countries applying the LRF, the criterion is purposed on the limit for the release of radioactive material. Cs137 100TBq corresponds to 0.1% of core inventory of an 1800MWt nuclear power plant. The reason why Cs137 is defined is that it requires long-term relocation of local population. It is also considered that fall-out would be small when 100TBq spreads to 100 km^2. Thus, the criterion of Cs137 100TBq is used neither to cause health hazards to public nor to restrict the use of land and water. [3,4]
On the other hand, in 1986, US policy statement [1] suggested that the frequency of large release should not exceed 10^{-6} per year. However, SECY-93-138[10] suggested that the LRF is conservative than safety goals, and hence the effort for defining large release should be terminated. Subsequently, they adopted LERF instead of LRF.

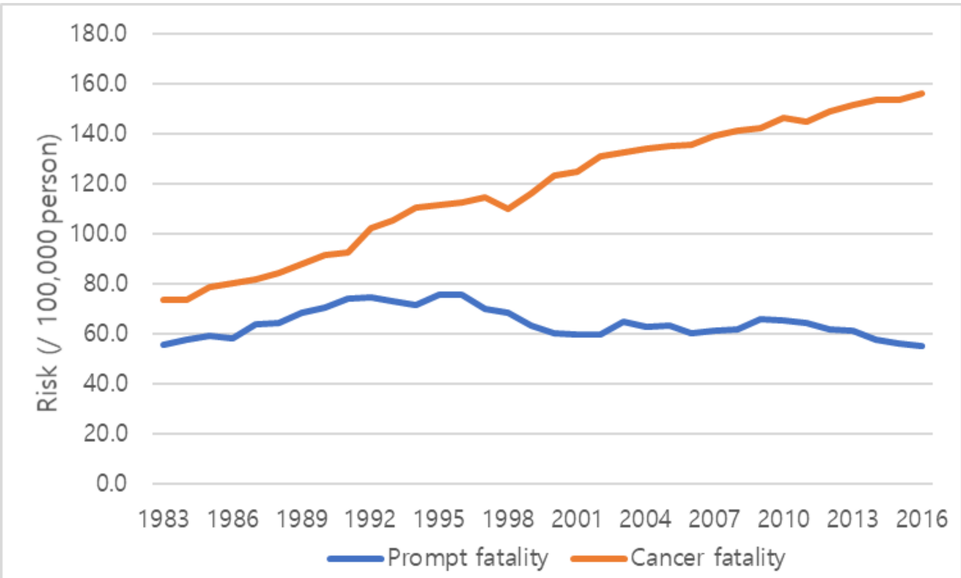
2.2. Relationships

Among the prompt and cancer fatality risks, there are several assessments that safety goal of prompt fatality is more conservative. It is suggested that cancer fatality is generally lower than safety goal when the safety goal of prompt fatality is achieved in NUREG-0880[8] and policy statement [1]. It can be seen that the margin of safety goal for prompt fatality is smaller than that for cancer fatality in NUREG-1150 which performed risk analysis. [11]
Subsidiary criteria such as CDF and LERF, are used for assisting prompt fatality and cancer fatality safety goals, which require large-scale risk analysis. That is, if CDF and LERF are met, it is considered that the safety goals for the prompt and cancer fatality are also met. CDF and LERF can be obtained as a result of level 1 and 2 PSA, and prompt and cancer fatality risk can be regarded as a result of level 3 PSA. [12] They can reduce uncertainty by replacing the prompt and cancer fatality risks which requires much efforts to evaluate. They also help to design the actual function or system. [13]
The concept of release is defined primarily as a quantitative safety goals. The criteria for release are LERF, LRF, SRF, and so on. LERF is mainly used to support safety goals of prompt and cancer fatality in the US and Korea, while LRF is used in place of safety goals of prompt and cancer fatality in Canada, Finland and Sweden and so on. SRF is one of Canada's quantitative health objectives. The definition of large early release is defined in several different ways and it is more qualitative. For example, the definition generally includes significant or large release, rapid release, unmitigated release, before off-site protective measures, and so on. However, the definition of large release and small release are absolute magnitudes of radioisotope release. For example, Cs137 100TBq is used as large release and I131 1000TBq is used as small release. [3]

3. Analysis of quantitative safety goals

3.1. Examination of prompt and cancer risks

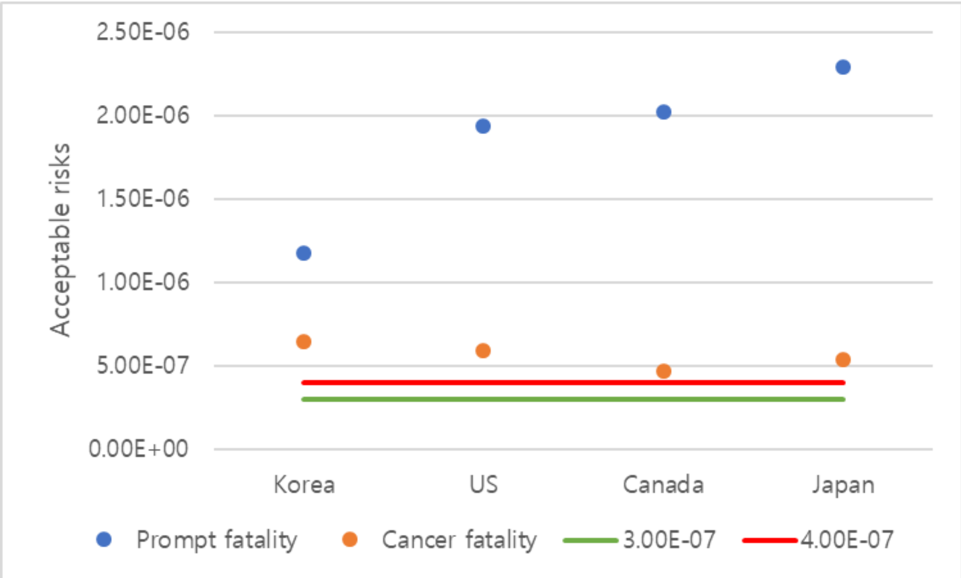
Figure 1: Prompt and cancer fatality in Korea



According to the calculation of NUREG-1860[13], prompt and cancer fatality risk are $3x10^{-7}$ per year and $4x10^{-7}$ per year when CDF is 10^{-4} per year and LERF is 10^{-5} per year. In this calculation, the conditional probability of an individual's prompt fatality within 1 mile is assumed as 0.03 and conditional probability of an individual's cancer fatality within 10 miles is assumed as 0.004, which

are largest value of results of NUREG-1150 [11]. In 1997, the accident death rate in the US was about $5x10^{-4}$ per year [15] and the cancer death rate was $19x10^{-4}$ per year [8]. Applying 0.1% ratio, the safety goals would be $5x10^{-7}$ per year an $2x10^{-6}$ per year for prompt and cancer fatality. That is, the prompt and cancer fatality risk satisfy the safety goals when CDF and LERF are satisfied.
On the other hand, according to the data of Korea National Statistical Office, general accident fatality and cancer fatality are shown in Figure 1. In this case, the safety goals for the prompt fatality and cancer fatality risk are about $6x10^{-7}$ and 10^{-6}. The prompt and cancer risks, which have 10^{-4} per year of CDF and 10^{-5} per year of LERF, satisfy the safety goals of them.

Figure 2: Comparison of prompt and cancer fatality risks



In the Figure 2, there are acceptable risks of prompt fatality due to general accident and cancer fatality due to other causes in several countries. The data of prompt and cancer fatalities are obtained from the national statistical data in Korea. In other countries, the data are obtained on fatality from World Health Organization(WHO) and obtained on the total population from United Nations(UN). There are also the acceptable risks when 10^{-4} per year of CDF and 10^{-5} per year of LERF are met. The acceptable risk corresponding to criteria of CDF and LERF is less than the acceptable risks from general accident and cancer in most countries. Thus, it is confirmed that the CDF and LERF is appropriate subsidiary criteria.

3.2. Effect of Cs137 release

Unlike the risk of prompt and cancer fatalities, the Cs137 is applied as a criterion for limiting land contamination or restriction of water use. Therefore, it is important to estimate the degree of influence of Cs137 100TBq on people by evaluating total acute bone dose and groundshine dose. The degree of influence of Cs137 1,000TBq is also estimated to compare with that of Cs137 100TBq.

3.2.1. RASCAL code

For analysis of Cs137 100TBq release, consequence analysis is performed with Radiological Assessment System for Consequence Analysis(RASCAL) code version 4.2. RASCAL code is designed to provide rapid dose assessment for emergency response purposes. It calculates the amount of the radioactive material release to the environment and converts it to doses. The results are compared to Environmental Protection Agency (EPA) protective action guidelines (PAGs) to

determine whether the public should evacuate or shelter. In this analysis, ‘time core is uncovered’ is used as the source term type and containment leakage is used as the release path.
The source term which depends on reactor power and burnup was calculated with SAS2H control module of SCALE 4.4a. The calculation of the released radioactive material is divided into several compartments such as fuel and containment. That is, the release from the core to containment and the release from containment to the environment are calculated. During the calculations, decay, removal function such as containment sprays and natural process, and ingrowth are also considered. At that time, the inventory release fractions of cladding failure, core melt, and post-vessel melt refer to NUREG-1465[16]. These fractions are based on the large break loss of coolant accident without emergency core cooling system that results in quick core uncovery. On the other hand, transport, dispersion, and deposition of released radioactive material are also calculated through Gaussian Puff model and Plume model with meteorological data. The doses are estimated by applying dose conversion factors. [17]

3.2.2. Results of RASCAL analysis

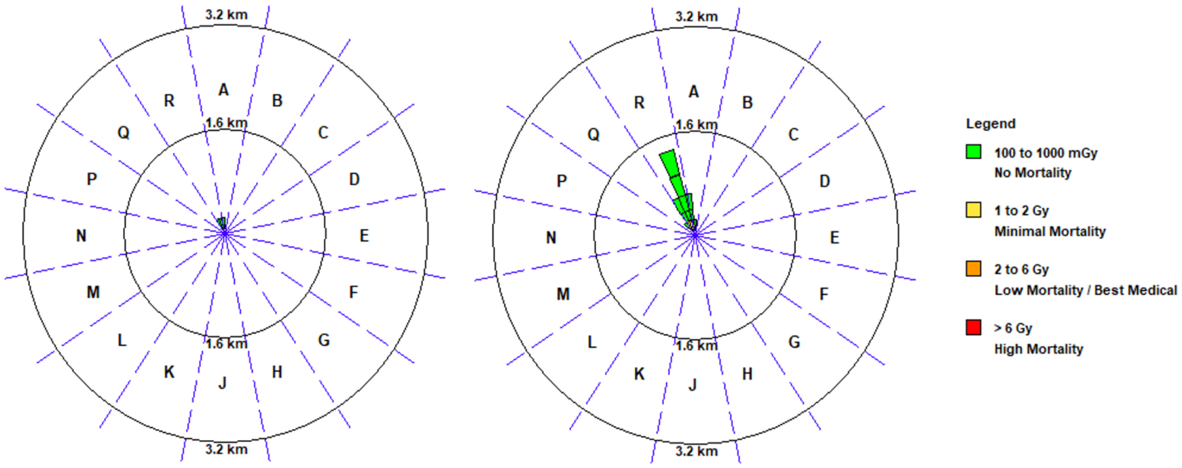
It is assumed that core damage and containment leakage occur at a 1400 MWe nuclear power plant, and then $2.5\text{x}10^{16}$ Bq of radiological materials which contain 100 TBq of Cs137 is released. It is also assumed that the core is not recovered and containment spray is not available. Nature processes such as gravitational settling is considered as reduction factors. Meteorological data are collected from the Meteorological Agency in the period from 2015 to 2017. Based on this data, average temperature and wind speed are calculated and no precipitation is assumed for the analysis. Atmospheric stability can be estimated in the code by relation with precipitation and wind speed, which is based on Turner[18]. The meteorological data used for the analysis are shown in Table 2.

Table 2: Meteorological data

Wind Direction From [deg]	Wind Speed [m/s]	Stability	Precipitation	Air Temperature [℃]
158	3.1	E	No	15.4

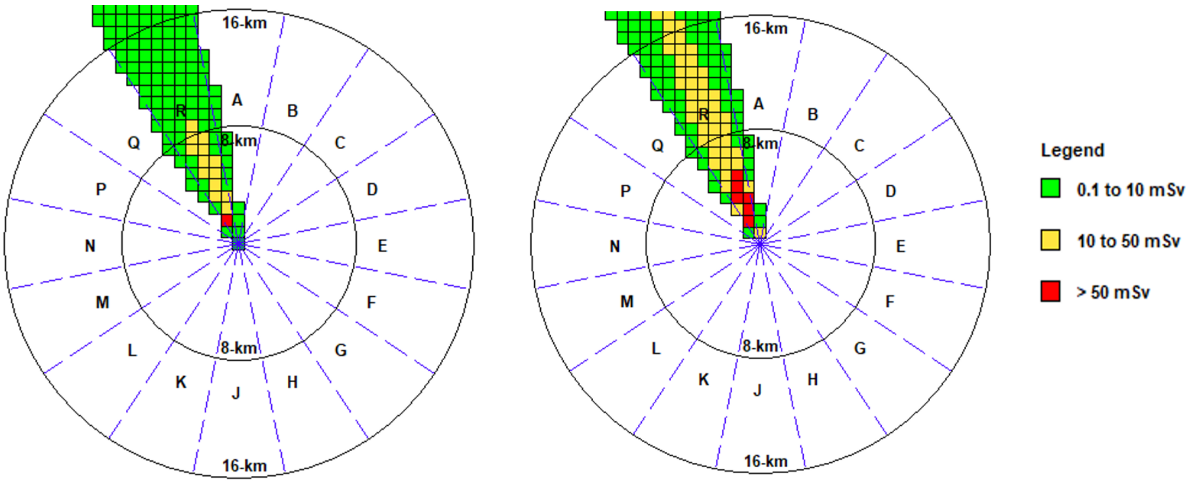
Figure 3 shows the total acute bone dose for the release involving Cs137 100TBq. The green region is for 0 to 100 rad where minimal health effect such as no nausea, no vomiting, and no fatality is expected. The effect of 100 to 200 rad which is the yellow region in Figure 3 would involve nausea or vomiting with 5 to 50%, minimal decrease in lymphocyte count, and minimal fatality. However, in the assumed accident involving the release of Cs137 100TBq, only the green region is present. When Cs 137 1000TBq is released, some yellow region begins to appear. Thus, the release involving Cs137 100TBq has little impact on the health of individuals.
RASCAL also provides groundshine dose calculations. Groundshine dose is the sum of the external doses from the radionuclides on the ground surface. It means that after surface contamination, in spite of no airborne contamination, there may be groundshine dose. The groundshine dose can be obtained by integrating the sum of the surface concentration of radionuclides multiplied by the dose conversion factor and roughness factor over a predefined period. The results can be obtained for 4-days or any time period after release. As Cs137 100TBq release is set as a criterion for preventing the long-term effect of land and water contamination, the groundshine dose for 4-days is analysed. The surface roughness factor is assumed to be 0.82 in the groundshine dose calculations. The results for 100TBq and 1,000TBq of Cs137 release are shown in Fig. 4.

Figure 3: Total acute bone dose



100 TBq 1000 TBq

Figure 4: Groundshine dose for 4-days



100 TBq 1000 TBq

In Figure 4, the regions are separated depending on dose equivalent. The green region is for 0.1 to 10 mSv, the yellow region is for 10 to 50 mSv, and the red region is for more than 50 mSv. In the PAG Manual [19], sheltering in place or evacuation is recommended as protective action for 10 to 50 mSv projected dose over 4 days which is the sum of committed effective dose and effective dose including groundshine dose. Therefore, in the yellow and red regions belong to the PAG action recommendation. When Cs137 100TBq is released, it can be seen that most of the regions are green which means that PAG actions are not required, while several areas beyond the PAG criteria are noticed when Cs137 1,000TBq is released. From Figures 3 and 4, it can be seen that the release involving Cs137 100TBq is expected to result in ignorable fatality and limited land contamination.

4. CONCLUSION

By reviewing the safety goals established by several countries, prompt and cancer fatalities, and LRF are selected as the quantitative safety goals to be considered in this paper. The safety goals of a nuclear power plant are considered to be met if the quantitative criteria such as prompt and caner fatalities and LRF are met. This paper reviews and analyzes these quantitative safety criteria as well as CDF and LERF, which are subsidiary criteria for prompt and cancer fatalities.

The criteria for the prompt fatality and cancer fatality are based on 0.1% of the risks from all other causes. Cs137 100TBq criterion has its basis on 0.1% of the core inventory of a 1,800MWt nuclear power plant. Prompt fatality and cancer fatality risk criteria are intended to protect the health in the public, while the Cs137 100TBq criterion is more focused on the environment such as land and water. For example, the Finnish regulatory body also considers that there would be no acute health effect if the Cs137 criterion is satisfied. [3] It can be also noticed that Cs137 100TBq release would results in ignorable fatality from the analysis result of RASCAL code.

Looking at the relationship between objectives of the prompt and cancer fatality, there are suggestions that the health objective of prompt fatality is more conservative than health objective of cancer fatality. According to analysis of the Korea National Statistical Office, the risk of cancer fatality due to other causes is gradually increasing, and accordingly the margin for target value will gradually increase on the risk of cancer fatality. On the other hand, the risk of the prompt and cancer fatality requires large scale risk analysis, and hence the corresponding subsidiary criteria such as CDF and LERF could be used. It could be found that the prompt and cancer fatality risk criteria are met when the criteria of 10^{-4} per year of CDF and 10^{-5} of LERF are met. It can be said that the prompt and cancer fatality also meet the safety goals in Korea, which are updated in 2016.

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