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Original Article

Consistency issues in quantitative safety goals of nuclear power plants in Korea

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ABSTRACT

As the safety level of nuclear power plants (NPPs) relates to the safety of individuals, society, and the environment, it is important to establish NPP safety goals. In Korea, two quantitative health objectives and one large release frequency (LRF) criterion were formally set as quantitative safety goals for NPPs by the Nuclear Safety and Security Commission in 2016. The risks of prompt and cancer fatalities from NPPs should be less than 0.1% of the overall risk, and the frequency of nuclear accidents releasing more than 100 TBq of Cs-137 should not exceed 1E-06 per reactor year. This paper reviews the hierarchical structure of safety goals in Korea, its relationship with those of other countries, and the relationships among safety goals and subsidiary criteria like core damage frequency and large early release frequency. By analyzing the effect of the release of 100 TBq of Cs-137 via consequence analysis codes in eight different accident scenarios, it was shown that meeting the LRF criterion results in negligible prompt fatalities in the surrounding area. Hence, the LRF criterion dominates the safety goals for Korean NPPs. Safety goals must be consistent with national policy, international standards, and the goals of other counties.

1. Introduction

As the safety goals of nuclear power plants (NPPs) define the level at which an NPP is considered to be safe enough, establishing safety goals is important for the protection of the public, society, and the environment. For this reason, many countries have established safety goals for NPPs with different qualitative and quantitative criteria.

There have been several research efforts in the international community focusing on safety goals and their international harmonization. A report by the Organization for Economic Co-operation and Development/ Nuclear Energy Agency (OECD/NEA), NEA/CSNI/R(2009)16 [1], summarized the answers to a questionnaire on probabilistic safety criteria including safety goals from thirteen nuclear safety organizations and six utilities. They concluded that probabilistic safety criteria can be grouped into four categories: (1) core damage frequency (CDF); (2) release frequencies, such as large early release frequency (LERF), large release frequency (LRF), and small release frequency (SRF); (3) frequency of doses; and (4) criteria on containment failure frequency (CFF). A report by the Reactor Harmonization Working Group of the Western European Nuclear Regulators Association (WENRA) [2], proposed seven qualitative safety objectives for new reactors and the associated candidate quantitative safety targets. A report by the OECD/NEA Multinational Design Evaluation Program (MDEP) Safety Goals Subcommittee [3], reviewed the high-level safety goals in different countries and concluded that the framework should have a hierarchical structure of safety goals that incorporate an extended defense-in-depth approach. Bengtsson et al. [4] also summarized how safety goals are defined in different ways in different counties. Technical meetings organized by the International Atomic Energy Agency (IAEA) [5] were held to promote greater understanding, harmonization, and communication of the use of safety goals. There have also many individual studies on safety goals such as Saji [6,7], Li et al. [8], and Heinz-Peter [9].

Multiple NPPs are typically built on the same site for economic and other reasons. Approximately 80% of NPP sites in the world have two or more NPP units. After the Fukushima accident, there has been a growing interest in evaluating the risks from multiple NPP units, as can be seen in the international workshop on multi-unit probabilistic safety assessment (PSA) [10]. Vecchiarelli et al. [11] discussed the proposal regarding site-wide assessment of NPP risks and site safety goals. Yang [12] indicated that many countries revisited their NPP safety goals after the Fukushima accident and

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that Korean safety goals need to consider multiunit aspects. Heo et al. [13] discussed the unique nature of Korean multi-unit NPPs and the technical issues associated with multi-unit PSA. Modarres et al. [14] suggested three options for defining large release frequency (LRF) as follows: (1) a release with at least one offsite fatality, (2) absolute or relative quantities of radio nuclides released, and (3) the condition of systems at the time of release. Modarres et al. [15] discussed multi-unit quantitative health objectives (QHOs) and their surrogate metrics. Hudson and Modarres [16] presented an approach for estimating multi-unit risk metrics for comparison with QHOs and showed that sufficient margins still remained in QHOs after including the contributions from two unit accidents.

As the need for the development of safety goals for multi-unit NPPs is discussed in the technical community, this paper reviews the safety goals of NPPs in Korea in relation to those of other countries, analyzes the logical relationships among them, and highlights consistency issues so that safety goals for NPPs can be set in a more reasonable and consistent manner, especially in future discussions considering multi-unit and site-level aspects.

2. Safety goals for nuclear power plants

2.1. Hierarchy of safety goals

There is a general consensus that safety goals are best represented using a hierarchical structure. An OECD/NEA report, NEA/CSNI/R(2009)16 [1], utilized a hierarchical structure with three levels: (1) society level, (2) intermediate level, and (3) technical level. Another OECD/NEA MDEP report [3] proposed a hierarchical structure with four categories: (1) top-level safety goals, (2) high-level safety goals, (3) lower-level safety goals and targets, and (4) technology-specific safety targets. The IAEA technical meeting [5] proposed a hierarchical structure with four categories: (1) top level (primary goal), (2) upper level (adequate protection), (3) intermediate level (general safety provisions), and (4) low level (specific safety provisions). Vecchiarelli et al. [11] provided a preliminary concept-level safety goal framework based on the hierarchical structure proposed in the IAEA technical meeting. In the United States, a hierarchical structure is used with three levels, namely (1) qualitative safety goals, (2) quantitative health objectives, and (3) subsidiary criteria.

As observed in the abovementioned hierarchical structures, the hierarchical structure of safety goals, in general, includes the following: (1) high-level qualitative safety goals, (2) intermediate-level quantitative safety goals, and (3) low-level subsidiary criteria. The high-level qualitative safety goals contain abstract concepts such as the protection of individuals, society, and the environment from the harmful effects of ionizing radiation. Quantitative measures are required because it is difficult to judge the degree of safety achievement by considering only the abstract concepts. For the intermediate-level quantitative safety goals, large-scale risk analyses are needed to ensure that such quantitative safety goals are met. The evaluation of the intermediate-level quantitative safety goals is substituted with the evaluation of the low-level subsidiary criteria. It is necessary that each stage in the hierarchy coincides with the high-level goals. It is also important to ensure that the qualitative safety goals are ultimately met.

2.2. Safety goals in various countries

Qualitative safety goals normally declare the protection of the public and environment from ionizing radiation and are expressed in different ways. Quantitative safety goals vary in different countries, which are summarized well in the international cooperative research efforts mentioned above [1,3,5], As indicated by Knochenhauer and Holmberg [17], quantitative safety goals can be defined in terms of the off-site consequences, radioactive release frequency, and core damage frequency, which correspond to Levels 3, 2, and 1 PSAs, respectively.

In some countries, quantitative safety goals are defined in terms of off-site consequences, while subsidiary criteria are defined in terms of the radioactive release frequency and core damage frequency. In the United States [18], the policy statement by the United States Nuclear Regulatory Commission (USNRC) defines two QHOs stating that the risks of prompt fatality and latent cancer fatality should be less than 0.1% of other risks in society. Therefore, it can be said that QHOs take on the role of quantitative safety goals and the subsidiary criteria for QHOs are set in terms of LERF and CDF.

In some counties, quantitative safety goals are defined in terms of the release frequency, while subsidiary criteria are set in terms of CDF. One important advantage of this approach is that the complexities and uncertainties associated with Level 3 PSA can be avoided, and clearer quantitative safety goals can be provided. In Sweden, by referring to SKI 7.1.24 1082/85 [19], NEA/CSNI/R(2009) 16 [1], provides the LRF criterion that the release of more than 0.1% of the inventory of the cesium isotopes Cs-134 and Cs-137 in the core of a 1800 MWt reactor shall be extremely unlikely. In Finland [20], limits for dose commitment and radioactive release are set depending on the operational states of NPPs, and the frequency of accidents releasing more than 100 TBq of Cs-137 is required to be extremely low. In Canada [21], quantitative safety goals are defined in terms of CDF, SRF, and LRF. It is notable that CDF is also placed at a high level in quantitative safety goals instead of being a subsidiary criterion.

In some countries, such as Korea and Japan, quantitative safety goals are defined in terms of both offsite consequences and the release frequency. The safety goals in Korea are explained in greater detail in the following section. In Japan [22,23], quantitative safety goals are defined such that the risks of prompt fatality and latent cancer are less than a fixed value of 1E-06 per reactor year instead of amounting to a small percentage of other risks in society. In addition, subsidiary criteria (called performance goals) are given in terms of CFF and CDF. While other countries apply stricter standards to new NPPs, Japan applies the same criteria for existing and new NPPs. Recently, Japan also introduced another quantitative safety goal stating that the frequency of the release of Cs-137 higher than 100 TBq during a nuclear emergency should be less than once in one million years.

Fig. 1 summarizes the quantitative safety goals of different countries and their corresponding PSA levels. When safety goals are defined in terms of multiple risk metrics like the cases of Korea and Japan and hence correspond to multiple PSA levels, it is important for the safety goals to be consistent with each other.

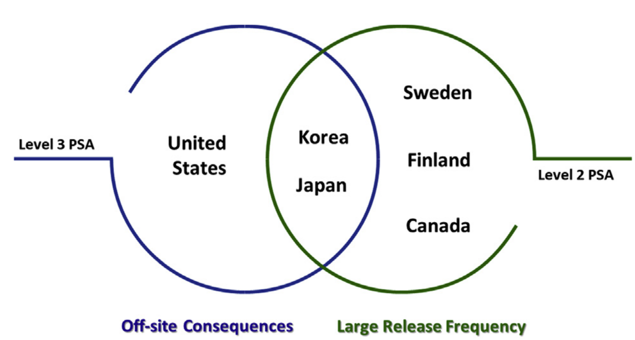


Fig. 1. Quantitative safety goals in different countries.

3. Safety goals in Korea

3.1. Historical perspective

Discussions on the establishment of the safety goals in Korea started in 1990s. The Nuclear Safety Policy Statement was announced in 1994 [24], which provided the policy direction to pursue an international level of safety and establish quantitative safety goals. Kim et al. [25] proposed a combination of QHOs and subsidiary criteria similar to those of the United States and concluded, based on a preliminary analysis of Korean statistical fatality data in 1999, that CDF and LERF are in comparable levels with those provided by IAEA and USNRC. The policy for severe accidents in NPPs [26] defines quantitative safety goals as QHOs for early fatality risk and latent cancer fatality risk to be less than 0.1% of total risks. After the Fukushima accident, there was a growing need to enhance the safety of NPPs, and quantitative safety goals were formally established as a Nuclear Safety and Security Commission (NSSC) notification [27].

High-level qualitative safety goals in Korea are specified in the Nuclear Safety Act as basic principles for nuclear safety management, which include the protection of people and the environment from the harmful effects of ionizing radiation. Intermediate-level quantitative safety goals in Korea are provided in the NSSC Notification and consist of two QHOs and one LRF criterion.

3.2. Two QHOs and their subsidiary criteria

QHOs consist of the objectives for prompt fatality risk and latent cancer fatality risks. The QHOs are defined in such a way that the risks of prompt and latent cancer fatality from an NPP should be less than 0.1% of the total risks, similar to the QHOs of the United States. Low-level subsidiary criteria are provided in a regulatory guide and consist of the CDF being less than 1E-04 per reactor year and LERF being less than 1E-05 per reactor year, while stricter target values, which are one-tenth of those of existing NPPs, apply to newly constructed NPPs. It is explained below why meeting the subsidiary criteria (CDF and LERF) generally ensures that the QHOs are met.

The prompt fatality risk can be roughly estimated by multiplying LERF with the conditional probability of early fatality (CPEF), which is the conditional probability of an individual becoming a prompt (or early) fatality for a nuclear accident with radioactive release. The cancer fatality risk can be roughly estimated by multiplying the large late release frequency (LLRF) with the conditional probability of latent fatality (CPLF), which is the conditional probability of an individual becoming a latent fatality for a nuclear accident with radioactive release. In NUREG-1560 [28], CPEF was roughly estimated as 0.02 by assuming that 1/3 of the people in a 22.5° angular sector out to 1 mile could potentially suffer early fatalities. In NUREG-1860 [29], CPEF and CPLF were estimated to be 0.03 and 0.004, respectively, which were the largest CPEF (within 1 mile) and CPLF (within 10 miles) for internal initiators provided in NUREG-1150 [30] for the Surry PSA.

LERF can be roughly estimated by multiplying CDF with the conditional containment failure probability (CCFP). The CCFP is usually assumed to be 0.1 based on the results of Individual Plant Examination (IPE) [28] in the United States. If CDF is less than 1E-04 per reactor year, LERF is estimated to be less than 1E-05 per reactor year; hence, the prompt fatality risk is estimated to be less than the 3E-07 per reactor year (multiplication of CPEF and LERF). Because the QHO for the prompt and latent cancer fatality risks, which is calculated by multiplying 0.1% with the statistical fatality data, is normally higher than 5E-07 per year (multiplication of statistical accident fatality risk and 0.001) and 1E-06 per year (multiplication of statistical cancer fatality risk and 0.001), it can be stated that the QHOs can be met by ensuring that the subsidiary criteria of CDF or LERF are less than 1E-04 and 1E-05 per reactor year, respectively. The above relation among QHOs, LERF, and CDF is illustrated in Fig. 2.

3.3. Large release frequency criterion

The LRF criterion is defined in such a way that the frequency of nuclear accidents releasing more than 100 TBq of Cs-137 should not exceed 1E-06 per reactor year, similar to the LRF criterion of Finland and Canada. No low-level subsidiary criterion is provided for the LRF criterion.

According to Orkent [31], WASH-1270 [32], published in 1973, suggested that the frequency of nuclear accidents resulting in individual dose exceeding 25 rem should be less than 1E-06 per reactor year. USNRC's Policy Statement on Safety Goals in 1986 also provided a general performance guideline that the LRF should be less than 1E-06 per reactor year. However, in SECY-93-138 [33], the staff concluded that the LRF criterion would be several orders more conservative than QHOs and recommended the termination of the development of the definition of large release. Later, in SECY-97-077 [34], the staff proposed a LERF guideline of 1E-05 per reactor year, which ensures that prompt fatality QHO is met without undue conservatism, as explained in Section 3.2. In SECY-00-0077 [35], the staff recommended incorporating a LERF subsidiary goal of 1E-05 per reactor year to the safety goals while deleting their reference to the general performance guideline so that the safety goal policy may have a better foundation.

There was also a proposal to promote CDF as a fundamental safety goal along with QHOs. However, it has not been approved owing to the concerns that the safety focus may change. USNRC decided to not adopt the LRF after many discussions and to use CDF and LERF as subsidiary criteria. The above discussions on LRF in the United States are summarized in Table 1.

As mentioned in Sections 2.2, LRF criteria are used as quantitative safety goals in Sweden, Finland, Canada, Japan, and Korea. In these countries, a large release is defined or roughly characterized as a radioactive release involving more than 100 TBq of Cs-137.

In Sweden, the safety goal for release was defined with the aims that long-term ground contamination of large areas shall be avoided, and there shall be no short-term fatalities in acute radiation syndrome, according to NEA/CSNI/R(2009)16 [1]. The former aim is achieved by meeting the 0.1% of Cs-134 and Cs-137 inventory criteria discussed in Section 2.2, which is equivalent to about 103 TBq of Cs-137, according to Knochenhauer and Holmberg [17]. The latter aim is achieved by limiting the radioactive release below 1% of the inventory of a 1,800 MWt reactor core, excluding noble

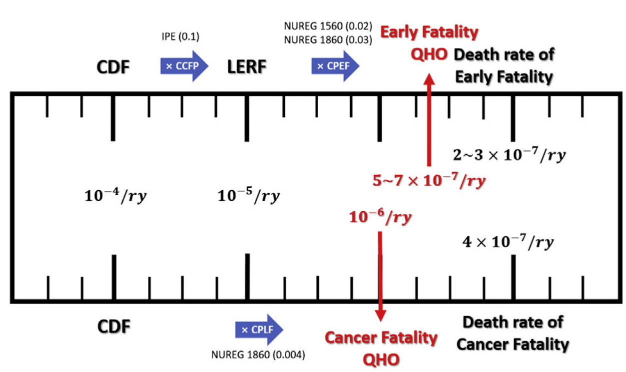


Fig. 2. . Relation among QHOs, LERF, and CDF

Table 1
Discussion on LRF in the United States.

Year	Document	Contents
1973	USNRC(AEC)WASH-1270	$f_{\substack{individual\ dose\\ exceeding\ 25rem}} < 10^{-6}/ry$
1986	USNRC's Policy Statement	General performance guideline (LRF < $10^{-6}/ry$)
1993	SECY-93-138	'LRF<$10^{-6}/ry$' is conservative than QHO.Terminate to define Large Release.
1997	SECY-97-077	LERF < $10^{-5}/ry$
2000	SECY-00-0077	'LERF < $10^{-5}/ry$' corresponding to the Reg. Guide 1.174 and the Regulatory Analysis Guidelines.Disapproval of elevation the CDF as fundamental goal.

gases.

In Finland, the radioactive release from a severe accident is limited so that it does not cause acute harmful health effects to the population nearby or any long-term restrictions on the use of the area, according to YVL 7.1 [20]. The Cs-137,100 TBq criterion is applied to satisfy the requirements for the long-term effects (long-term restrictions on the land use).

In Canada, three quantitative safety goals are defined for CDF, SRF, and LRF. The safety goals for SRF and LRF are defined because greater releases may require temporary evacuation and long-term relocation of the local population, respectively, according to REGDOC-2.5.2 [21]. The numerical values of SRF and LRF were chosen as the limits that would not significantly contaminate areas larger than the plant exclusion zone.

In summary, the LRF criterion of Cs-137,100 TBq is defined mainly for limiting long-term restrictions on the land use owing to contamination and basically assumes no prompt or latent cancer fatalities. Because QHOs are defined to be less than 0.1% of the total risks to limit the prompt or latent cancer fatality risks, it is clear that the LRF criterion is more conservative than QHOs. In particular, the LRF criterion is more conservative than the QHO for limiting prompt fatality risk, which is also normally known to be more conservative than the QHO for limiting latent cancer fatality risk.

4. Consequence analysis of 100 TBq Cs-137 release

A quantitative analysis of the effect of 100 TBq Cs-137 release on people in the vicinity and environment would be helpful in understanding the conservatism of the LRF criterion over QHOs. By simple calculation, it can be found that 100 TBq of Cs-137 is equivalent to 32 g. Seo and Shin [36], performed MAAP code analysis for a representative source term category of an OPR1000 NPP and concluded that the amount of Cs-137 released in the environment for each source term category is over 1,000 TBq, which is approximately 10 times more than the amount of Cs-137 specified in the LRF criterion.

Quantitative analysis is conducted on the accidents with a release of approximately 100 TBq of Cs-137 to analyze the effect of such a release from a 1400 MWe NPP by using a consequence analysis code, RASCAL (Radiological Assessment System for Consequence AnaLysis). RASCAL was developed by USNRC over 25 years and is currently used by the Protective Measures Team in the USNRC for making independent dose and consequence projections. NUREG/CR-6853 [37] compared radiological consequence codes including their pros and cons and found that the calculation results of MACCS2 [38], RASCAL [39], RATCHET [40], and ADAPT/LODI [41,42], were within a factor of two.

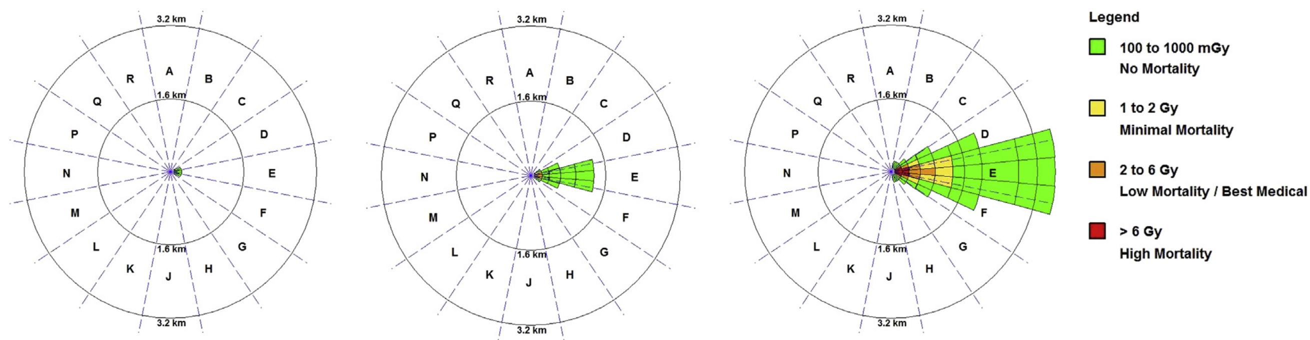
The models and methods used in RASCAL 4 are described in NUREG-1940 [39]. The core inventory is calculated from the normalized core inventories prepared with the SAS2H of SCALE (Standardized Computer Analyses for Licensing Evaluation) after being adjusted with burnup and reactor power. The coolant inventories are taken from ANSI/ANS 18.1–1999. The timing and fractions of core inventory release into the containment atmosphere or the coolant are taken from NUREG-1465 [43]. Potential reduction mechanisms, such as containment sprays, containment natural processes during hold-up, and partitioning during steam generator tube rupture (SGTR) for various releases pathways, are incorporated using reduction factors from NUREG-1228 [44] and others data sources. Atmospheric transport is modeled with a straight-line Gaussian dispersion model for the close-in area (2 miles by default) and a Gaussian puff model for the area beyond the close-in area, with consideration of atmospheric conditions such as wind direction, wind speed, stability, mixing layer thickness, and precipitation. Both dry and wet depositions of particles and gases are modeled with consideration of depletion, decay, and ingrowth of radionuclides. Then, the organ committed dose equivalent due to inhalation, dose equivalent due to the radionuclides deposited on the ground, and cloudshine (external gamma) doses are calculated, and the early-phase total effective dose equivalent is calculated as the sum of the three dose components for four days under the assumption that no protective actions are taken. Acute doses to red bone marrow, colon, and lung, as well as intermediate-phase doses due to ground contamination for the first year, second year, and 50 years after the release are also calculated.

The following eight different accident scenarios with two initiating events, large-break loss of coolant accident (LBLOCA) and steam generator tube rupture (SGTR), involving the release of 100 TBq Cs-137 are analyzed using RASCAL 4:

- LBLOCA with containment spray
- LBLOCA without containment spray
- LBLOCA with filter
- LBLOCA without filter
- SGTR with rupture below water level and release from condenser exhaust
- SGTR with rupture above water level and release from condenser exhaust
- SGTR with rupture below water level and release from safety relief valve
- SGTR with rupture above water level and release from safety relief valve

In the quantitative analysis with eight different accident scenarios involving the release of 100 TBq Cs-137, it is concluded that the consequence of the release is not significantly affected by accident scenarios, even though the nuclide compositions in the source term are slightly different in different scenarios.

The LBLOCA without containment spray and a containment leak rate of 0.23 vol percent per day is selected as a representative accident scenario. The accident results in the release of 100 TBq of Cs-137. Considering that the design leak rate is 0.1 vol percent per day, it can be said that any break in the containment may lead to the release of Cs-137 exceeding 100 TBq. It also means that, as long as



(a) 100 TBq (b) 1,000 TBq (c) 10,000 TBq

Fig. 3. . Total acute bone dose for 100 TBq, 1,000 TBq, 10,000 TBq of Cs-137 release.

the integrity of the containment is maintained, the release of Cs-137 can be limited below 100 TBq even after an LBLOCA with no containment spray.

Atmospheric conditions at the time of the accident are assumed to be the standard meteorology provided in RASCAL. They involve a wind direction from east to west, wind speed of 1.8 m/s (4 mph), Pasquill-Gifford stability class D, and no precipitation. The release height is conservatively assumed to be 10 m. A sensitivity analysis for varying wind speed and release height was also performed. Calculations are performed for 2 miles (3.2 km) of close-in area, and hence only straight-line Gaussian dispersion model is used for atmospheric transport.

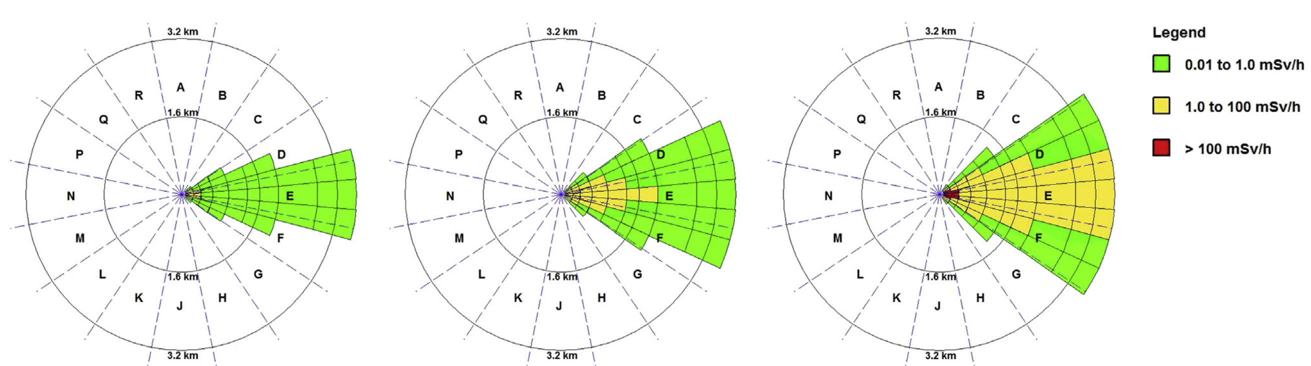
Fig. 3 shows the total acute bone doses, which represent the early fatalities due to the release, involving 100 TBq, 1,000 TBq, and 10,000 TBq of Cs-137. The early fatalities are relatively limited for the release involving 100 TBq of Cs-137, and they are still limited for the releases involving 1,000 TBq and 10,000 TBq of Cs-137. On the other hand, Fig. 4 shows the groundshine dose rates, which represent the contamination of the nearby land due to the releases, involving 100 TBq, 1,000 TBq, and 10,000 TBq of Cs-137. For the 100 TBq release, the land downstream of the wind is contaminated from 0.01 to 1.0 mSv/h, while the releases involving 1,000 TBq and 10,000 TBq of Cs-137 result in more contamination in the land downstream of the wind. In other words, the release involving 100 TBq of Cs-137 results in no or a negligible number of early fatalities and minimally contaminates nearby land in the downstream of the wind. By comparing Figs. 3 and 4, it is found that the quantitative safety goal for LRF is more conservative than that for early fatalities in Korea. In other words, the existence of the quantitative safety goal for LRF virtually makes the existence of the quantitative safety goal for early fatalities (and, in fact, latent fatalities) meaningless.

Fig. 5 and Fig. 6 show the total acute bone dose and groundshine dose rate for different release heights (from 10 m to 70 m) and wind speeds (from 1 m/s to 9 m/s). By considering that Figs. 3 and 4 show the results for the release height of 10 m and wind speed of 1.8 m/s, it can be said that the conclusions provided above were derived based on conservative consequence analysis results .

5. Conclusions

The safety goals of an NPP define the level of safety the NPP must be maintained. Safety goals are important factors when drafting the national policy on nuclear safety; different countries have different safety goals in their policies. Quantitative safety goals for NPPs in Korea were formally defined in 2016 in an NSSC Notification. Especially after the Fukushima accident, there has been a gradual increase in the concerns raised by society regarding multi-unit risks; this has led to discussions on safety goals for multiple NPPs in the technical community.

Safety goals are represented with hierarchical structures, which include (1) high-level qualitative safety goals, (2) intermediate-level quantitative safety goals, and (3) low-level subsidiary criteria. In Korea, the safety goals of NPPs have a hierarchical structure, as recommended by the international community. High-level qualitative safety goals are defined in the Nuclear Safety Act.



(a) 100 TBq (b) 1,000 TBq (c) 10,000 TBq

Fig. 4. . Groundshine dose rate for 100 TBq, 1,000 TBq, 10,000 TBq of Cs-137 release.

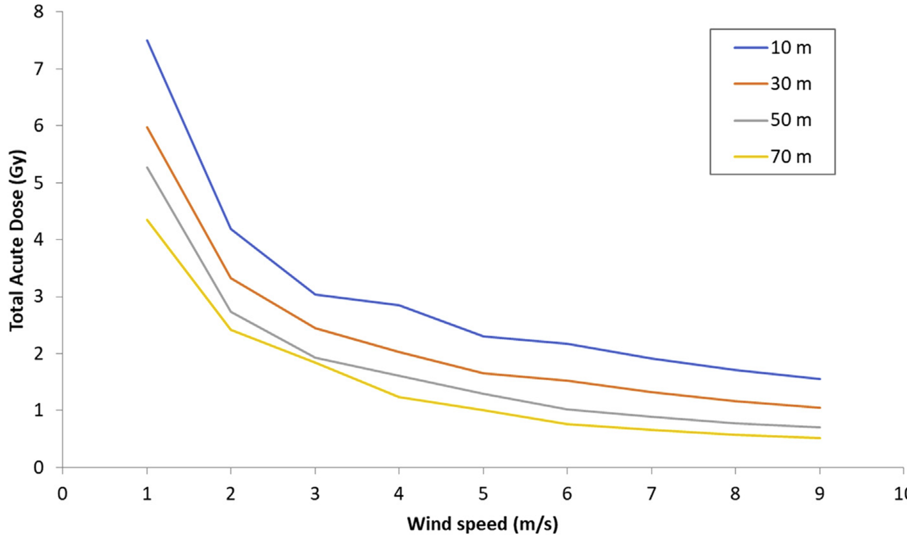


Fig. 5. . Total acute bone dose for different release heights and wind speeds.

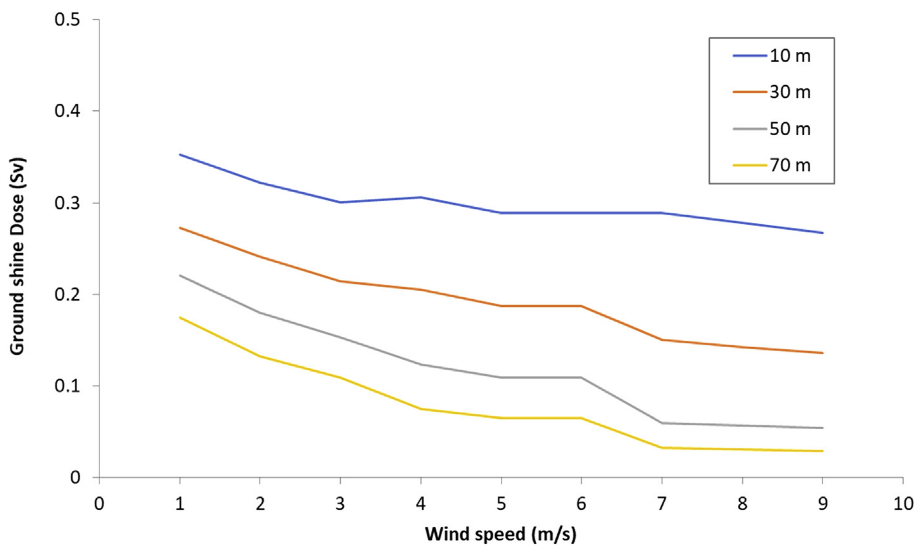


Fig. 6. . Groundshine dose rate for different release heights and wind speeds.

Intermediate-level quantitative safety goals defined in the NSSC Notification consist of two QHOs and one LRF criterion. Low-level subsidiary criteria are defined in regulatory guides as performance objectives, and they consist of CDF and LERF criteria. On analyzing the relationships between QHOs, LERF, and CDF, the results clarify why satisfying the subsidiary criteria on the CDF and LERF guarantees meeting the QHOs. It is noted that the LRF criterion does not have subsidiary criteria like CDF and LERF for QHOs.

Quantitative safety goals are defined in terms of off-site consequences (which correspond to Level 3 PSA) in some counties, whereas in other countries, these goals are defined in terms of radioactive release frequency (which corresponds to Level 2 PSA). In Korea, quantitative safety goals are defined in terms of both offsite consequences and the release frequency. Therefore, the safety goals correspond to both Level 3 and 2 PSAs. It is very important for the safety goals, as the basis for national policies on nuclear safety, to be consistent with each other.

From the review of the safety goals of those countries that adopt the LRF criterion, it is noted that the purpose of the LRF criterion is to limit land contamination and resultant restriction on land use, rather than to limit early or latent cancer fatality risks due to radioactive release from a severe accident. Therefore, it could become evident that quantitative safety goals (QHOs and LRF criterion) are not compatible with each other and the LRF criterion is significantly more conservative than QHOs. The consequence analysis in Section 4 shows that the release involving 100 TBq of Cs-137 results in zero or a negligible number of early fatalities, and it minimally contaminates nearby land in the downstream of the wind. It also needs to be noted that the LRF criterion was not adopted in the United States because it was significantly more conservative than the existing quantitative safety goals, QHOs.

Safety goals have important roles in guiding the national policy on nuclear safety. A careful, systematic approach with considerable review and study on safety goals is necessary to ensure that they are in line with the national policy, compatible with international standards, and harmonized with the goals set by other counties. This research is expected to contribute to future discussions on ensuring the consistency of safety goals for NPPs in Korea and other countries so that the safety goals for NPPs can be set in a more reasonable and consistent manner, especially when multi-unit and site-level aspects are involved.

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