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A Preliminary Study on the Achieved and Extendable Concepts of Nuclear Safety to Improve the Social Acceptance in Korea

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1. Background: extension of the concept of safety

Although the benefits and economics of nuclear technology are clear, controversy over its acceptance in Korea remains. The controversy over the acceptance of nuclear technology is mainly about the safety. The controversy is still expanding as the change and expansion of safety concept are taking place due to the recent development of advanced technology and social change. This seems to be a task that will continue for new revolutionary reactors such as SMR, which are expected to be the next generation of nuclear systems.

This paper investigates the conceptual scope of safety necessary to improve the social acceptance of next-generation nuclear power. First, a discussion on the unique characteristics of nuclear safety and the conceptual scopes of safety achieved in the field of nuclear power are reviewed. Based on this, the conceptual scope of nuclear safety necessary to improve the social acceptance of nuclear power is investigated. The current status of awareness and direction of demand for nuclear safety were investigated through surveys and interviews with residents around a nuclear facility. The conceptual areas of safety necessary for future nuclear power are presented as ratings and priorities

2. Characteristics of Nuclear Safety

Controversy over the safety of nuclear technology is natural in that the more advanced the technology, the more two-sided it can be. However, safety includes several additional aspects that go beyond the general concerns that new technologies inevitably face.

- First, it is natural because the large drop applied to nuclear energy-intensive characteristics and power generation can fundamentally mean hazard.
- Second, anxiety about energy that cannot be experienced on the everyday life has a great influence. This is because anxiety is further amplified by the invisible nature and lack of control of energy production. It has influenced on social acceptance.
- Third, the large-scale problem works with both sides. Nuclear power is a typical large-scale energy system, and it shows great advantages in terms of cost in terms of economies of scale in the classical sense. However, this can act as a large impact or social disaster on the power supply chain or energy base due to the enormous impact of accidents and failures.
- Fourth, nuclear power has high safety sensitivity while it is difficult to learn experience due to its high reliability. The high reliability of nuclear power is the reason why empirical learning, which is important in general safety, becomes difficult.
- Fifth, nuclear safety is irreversible. It is known that general safety can be restored to its original state in significant areas and at significant levels, whereas this is relatively not the case. Uncertainty that radiation can have a long-term impact on a wide range of areas and generations makes safety extremely sensitive.

3. Safety Achieved and Required in Nuclear

The unique safety characteristics of nuclear power had a great influence on the development of nuclear technology. Securing thorough safety from the early stages of nuclear technology development was a priority. Additional safety efforts have served as an opportunity to achieve pioneering technology development and continuous development in safety. The following is a classification of the conceptual areas of safety based on safety experiences and history in the nuclear field.

- *Death and Injury of workers*
- *Functional Reliability of Parts and Systems*
- *Impact on the Electric Power Economy*
- *Ssocial Shock and Burden*
- *Environmental and Long-Term Safety*

It is no exaggeration to say that the demand for safety in nuclear power has actually been imposed by the nuclear power system itself. In a situation where it is difficult to understand the specific substance of the expected danger in nuclear power outside of nuclear power, the nuclear power system has set its own requirements and satisfied itself to overcome the danger and achieve safety. A thoroughly conservative approach to the human impact of radioactive materials is beyond the common-sense understanding of the public.

2.1 Quality based Safety

For safety, the quality and reliability requirements of all elements used in nuclear power are strong enough to have a separate term, Nuclear Grade. High-quality-based safety through strong quality control techniques and systems may be the earliest contribution of the nuclear industry to other industries. This includes the domains of financial and investment safety.

2.2 Reliability based Safety by Critical Elements

In addition, reliability standards for nuclear power are very thorough and high, from parts to systems. High levels of reliability standards and frequent test inspections have become basic requirements for high reliability industries. In addition, strict procedural-based duties cause nuclear power to be viewed like a military field. However these turned out to be *Not-Enough* [3,4]

2.3 Functional Safety and Ssafety Designs

Parallel, redundant, and contrast designs to achieve the functional reliability of systems in nuclear power are prototypes of functional safety design. Additional safety features are also close to half of all nuclear designs to actively cope with risks. The nuclear industry has been trying to achieve below the 'fate level' the level of risk that nuclear systems can pose to the general public. Inevitably, such as the danger of natural disasters such as floods and thunderstorms, it is inevitable that the public can accept it.

Above all, many of these safety requirements currently applied in the nuclear field are very detailed and conservative, and other high-reliability industries have only recently recognized and referred to their effectiveness. For example, the semiconductor industry, which experienced enormous losses due to instantaneous total loss of electric power, is only now introducing the techniques and conservative designs to prepare for all power loss of nuclear power plants.

2.4 Human (and Organizational) Factors Safety

Finally, the technical response in the nuclear field to human errors that ultimately threaten safety is the most advanced field. In the nuclear field, the ergonomic perspective that humans are a key factor in determining the safety of the entire system was introduced early. This perspective, which is involved in high-quality and reliable hardware, rapidly spread to the TMI thinking experience in 1979, and became the basis for the nuclear revival with the development of MMIS (Man-Machine Interface System) based on computer technology. This can be seen as playing a pioneering role in the trend of UI/UX interface technology in determining the success or failure of element technology, as shown in the recent development of smartphones.

Nuclear safety in terms of human factors has been greatly expanded through the Chernobyl accident in 1986 and the Fukushima accident in 2011. Compared to previously dealing with factors mainly related to individual job functions in terms of human factors, safety requirements have been applied to a wider range of teams, organizations, and society's safety culture.

These pioneering safety efforts in the nuclear field have a great impact on other high-confidence industries, contributing greatly to properly recognizing and determining the priorities of efforts required for the solid development of advanced new technologies.

2.5 Societal Safety including Environmental Radiation and Climate Change Concerns

The discussion of nuclear safety has emerged greatly from the perspective of the environmental and climate crisis. Nuclear power comes from a new source that is different from traditional physical or chemical energy. Therefore, it is the external energy of the human energy ecosystem, which has been built mainly on carbon energy from solar power. It can be an external way to independently supplement various problems and crises occurring in the traditional energy ecosystem. In a situation where the environmental crisis caused by the loss of control over temperature rise caused by abuse of carbon-based energy is an important technical alternative to ensuring human safety.

On the other hand, however, nuclear waste is still in a situation where human-kind has not yet developed sufficiently appropriate treatment plans. Nuclear waste is a serious environmental threat and is also a risk factor that is difficult to easily accept from a social safety perspective. The top safety requirement for nuclear power is safety from an environmental perspective. By converting permanent risks to be acceptable to the general public, it is necessary to solve the nature of nuclear power acting as a safety threat.

This means that it is urgent to go beyond the traditional reactor core type and develop new types or to develop a break-through technology such as nuclear species transformation for waste disposal. However, it is difficult to relatively examine the priorities of investment for safety because it is a deterministic task for safety. It becomes to social concerns and conflicts.

3. Nuclear Safety Required for Public Acceptance and Behavioral Scientific Perspective to Safety

Recently new requirements for nuclear safety have emerged as new demands and perceptions of safety have spread socially. Previous papers of Lee [5,6,7] reviewed changes on safety concepts and new requirements for nuclear safety. They discussed new safety perspectives and behavioral science approaches applicable to cope with new domains of safety concept.

3.1 Social Safety requirements: Social Acceptance

The explanation given by nuclear for the level of nuclear safety in this regard is relatively consistent. As a result of the expected level of risk comprehensively derived from various perspectives, the current nuclear power is sufficiently acceptable. Compared to any other risk (system), it is managed low enough, so it is not effective. However, socially, the risk obtained by engineering calculations in nuclear is not considered comprehensive, so it is not viewed as a sufficient basis for safety and safety decision making. There should be discrepancies in the concept and perspective of risk, though even a game-based trial has been proposed.[3,4]

Above all, the perspective of risk is fundamentally different. The risk to systems such as nuclear power plants is from a functional point of view. When functions are completed, risks have traditionally been presented in the form of death and injury rates in addition to economic loss calculated. A review of the history of nuclear safety and various safety concepts for social acceptance of nuclear power.

System Risk (R') ≠ Σ (Loss x Prob.) Risk: Expected Loss = Loss x Prob. System Risk (R) = Σ (Loss x Prob.)	(1)

3.2 Variety of Concepts of Safety and Risk

Safety means a state of no risk. ICE has described safety as 'Freedom from Hazards'. However, hazard includes everything that is expected in the future at various points of time from what is at hand. Also, it can vary greatly depending on what perspective is defined. Traditional safety has been dealt with around the possibility of completing required functions. In particular, it was concerned with losses and deaths and injuries caused by failure to fulfill preset functions. Therefore, the loss of life due to fundamental uncertainty was regarded as random, and the key was the top safety perspective that analyzed functional safety.

However, the need for fundamental changes in the safety concept based on functional reliability has been raised in the wake of shocking disasters such as the TMI nuclear accident, the Bhopal chemical plant accident, the Challenger explosion, the Chernobyl nuclear power plant fire explosion, the space shuttle Columbia explosion, the Deep-water Horizon oil probe explosion, oil leakage, and the Fukushima nuclear power plant accident. The following are several concepts presented to complement the existing safety concepts from various perspectives.(*variety of references not limited here[7]*)

- *Risk Society Paradigm*
- *Normal Accident Paradigm*
- *X-event and Big-One Paradigm*
- *Man-Technology-Organization Paradigm*
- *House of Cards Paradigm*
- *Safety II and Resilience*
- *Human Error 3.0 Paradigm*

The contribution to embodying the concept and substance of safety in the process of scientific and technological development is enormous. The concept of safety, which still remained a unique task in individual fields in the process of rapid technological development after the Industrial Revolution, was embodied by Heinrich and subsequent researchers in the 1940s. In the field of nuclear power, the possibility of comprehensive treatment was opened only by the concept of probabilistic risk demonstrated by Rasmussen in 1976. Above all, the risk can be calculated quantitatively promoted the development of a systematic technology dealing with safety along with the development of probability theory. Although nuclear was not the field that started this, it has led the development, showing that the effort of nuclear safety have been tremendous.

First, the probabilistic approach to the occurrence of danger is showing limitations. Risks assuming unintended randomness are identified as a stoppage process, so the probabilistic approach was effective. However, traditional concepts and approaches of safety show limitations to the issue of extreme low frequency to which probabilistic radioactivity is not applied. The concept of safety for ultra-long-term (more than 100,000 years) or ultra-low-frequency (less than a millionth) events frequently discussed in the nuclear field will require a review of the need for traditional safety and other aspects. (This is a situation similar to that of Newtonian mechanics no longer valid for microscopic atomic worlds and ultra-fast particles.)

Second, it is implicitly natural that safety is based on the present in terms of time. However, this is not clear and is not always fixed. For a particular point of view or stakeholder, safety can be selected based on a particular past point or expected state, not the present.

Third, items of risk or risk factors can be defined and classified in completely different ways depending on the stakeholder. Since risk is about value, an item that is important to a particular person or its size cannot be the same for others. Therefore, various criteria can be included in the concept of actual safety depending on the perspective of the stakeholder in the same field. The following are the various criteria that have recently been discussed as being able to be included in the conceptual scope of safety.

- *Sustainability*
- *Resilience*
- *Restorability*
- *Shock Impact to daily life*
- *Disgusting or Reluctance*
- *Self-management or self-control*
- *Environmental and health impacts*
- *Compliance with pre-appointments*

ISO and others have proposed new management standards to cover these various perspectives from ISO-9000 to 45000 series, but continuous expansion seems inevitable in the future as the times and concepts change. The UN and OECD have recommended embracing various perspectives of stakeholders in public decision-making such as nuclear safety. Risk is a neutral measure that combines loss and its possibilities, and is an effective measure of safety that can combine essentially different risks arithmetically. By synthesizing the expected future losses and presenting them in the size of anxiety, numerous perspectives and controversies related to safety could be integrated. However, the scope included in risks has changed (mainly expanded) with the development of technology and society.

Firstly, the risks calculated for safety mainly included the possibility of death or injury to people. Fatality, the rate of death, and the rate of labor loss are key items of classical risk considered the top priority.

Second, property loss along with death or injury can be said to be the most realistic risk factor. In classical risk calculation, risks related to human life are also specified as economic values in order to synthesize them as a consequential loss.

Third, the concept of a crisis such as a disaster is also being added to the risk. Large-scale accidents and disasters are beyond simple losses and are social and psychological shocks, so they need to be treated differently. In this case, the perspective of social costs is needed, and the costs and possibilities related to recovery, not losses, need to be included in the risk.

3.3 Alternative Approach to Risk and Safety based on Behavioral Science Perspective

Several fundamental limitations can be pointed out due to the limitations of the practical process at the same time as the range of factors included in risks highlighted as a comprehensive measure of safety is expanded around the nuclear field. Above all, a new approach is needed because the presentation of objective immutability or fixed absolute values for risks in nuclear systems contradicts actual safety awareness.

There are several aspects on the traditional definition of risk measure (1972 Thygerson, 1977 Tarrant) that could be discussed and modified by incorporating the behavioral science perspective (2018 Lee). [4]

At first, risk is extended to more than the traditional interpretation of expected loss. It can be re-interpreted into the subjective utility and the different values to the perspective applied (2003 Rasmussen). For example the loss can be extended more from the damage to the system investment to the negative happens and propagations beyond the system and the crew involved (refer to 1992 Rasmussen, 1997 Reason, 1992 Wickens).

Secondly, the real value of risk needs to be re-interpreted into a utility value rather than the objective cost and/or the investments. It means that the all the losses and their probabilities should be transformed by their own characteristics curves. Logistics curve is a typical one shown in following figure.

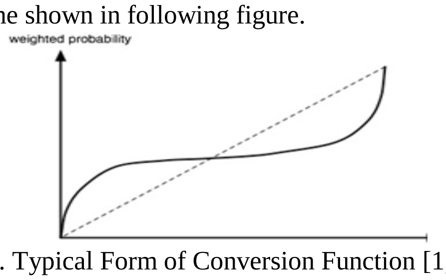

Figure 1. Typical Form of Conversion Function [1,5,6]

Thirdly, the postulated additivity on the risk accumulation may not applicable to the subjective utilities rather than the objective values of each risk. System risk can not be calculated by the simple arithmetic.

System Risk (R') ≠ Σ (Loss x Prob.)
Plausible Loss > Loss postulated in R of Eq.(1) **Plausible Prob. > Prob. postulated in R of Eq.(1)**

The risks in terms of utilities obtained from the persons and population groups show strong dependencies on their psychological and cognitive behavior. They are described from the early study on the *Allias' paradox* (1954) to the rather recent studies in behavioral science. The risk of expected loss can be scrutinized by the arguments that have been discussed in cognitive studies on the fallacies in decision making (1982, Wickens), the paradox in gambling choices (1954, Allais), and the heuristic and biases in judgments under risk (1974, Tversky and Kahneman). A study to demonstrate the utility perceptions was concluded by the so-called *Prospect Theory* (1979, Kahneman & Tversky) and the following simple graph (refer Fig. 2).

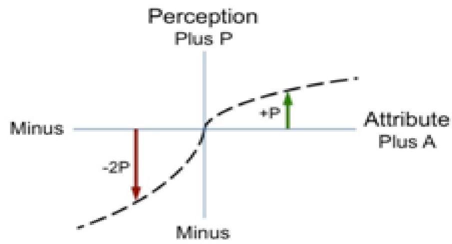

Figure 2. Typical Asymmetry of Gain/Loss [5,6,11]

In addition to the asymmetry of gain and loss, followings are the typical cognitive considerations from behavioral science. (refer to Tversky, Wickens[1, 12])

- *insensitivity near the extreme ranges*
- *anchoring to the first and the salience*
- *availability bias due to the recency and primacy*
- *marginality to the change*

Nowadays the utility interpretation on the expected values related to all decision makings in practice has become mandatory rather than recommended to various fields and people. (Dr. Kahneman profoundly has contributed to behavioral science of the changes and its prevailing applications after 1980's, and got a Nobel Prize in 2002 [1,11].)

The calculation of risk that is traditionally believed as *simply-additive* would be complicated by the risk perception behavior in practice. The risk values could not be simply additive anymore especially during the risk decision-makings and judgments. NIMBY shows the big discrepancy among the risk values perceived by me and others. Following revised equation can show a proposed modification from the traditional risk quantification (R) to the new one (R') by incorporating the behavioral science perspective to the definition of risk. (*refer to papers of Lee for details*[5,6,7])

Perceived Risk (R')=f({u(Loss)$_i$ x π(Pro.)$_j$ }$_k$)
✓u(Loss)$_i$ = utility value of Loss$_i$
✓π(Prob.)$_j$ = weighted prob. of Pro$_j$
✓f(Risk$_k$) = integration of Risk$_k$

'u' means utility function that might be convex for gain and concave for loss along the reference point selected by people in risk perceptions and decisions.
'π' means decision weight that may be a typical s-shape curve of conservatism.
∫ means the integral of risks rather than simple additive calculation.

4. Investigation of Safety Areas Required in the Nuclear Field

According to the drastic changes in the concept and domains of safety, the level of achievement of safety in the nuclear field and the safety areas expected or required in the future were investigated.

A set of basic data (n=20) were collected through rating questionnaire surveys and focus group interviews (GFI) targeting local residents living near a nuclear facility in Korea. And a simple statistics was applied.

A preliminary result of this survey can be brief as followings according to the different conceptual domains of safety in nuclear safety. No significant difference can be obtained between "achieved" and "required" safety of nuclear.

- *Fatality and Injury Safety: no big Concern*
- *Investment Safety: no big Concern*
- *Functional Safety: Acceptable*
- *Environment/Radiation Safety: Moderate*
- *Societal Safety: very limited and Demanding*

(Statistical data and results to be shown here)*

The data size and sampling of survey population might not be designed properly enough to obtained statistical power for the conclusions. However, the results can show that they recognize that nuclear safety is considerable in terms of functional safety based on reliability (i.e. RMAS). It also was found that other aspects of safety were still insufficient or required additional efforts. (*It can be statistically concluded that this was not related to the personal tendency toward nuclear power*.) In addition, it could have practical implications that the higher the interest and understanding of the latest nuclear facilities (such as waste disposal facilities) and new reactors (SMR and other types of). The more the need for a new range of nuclear safety was required in Korea, for especially public acceptance.

5. Conclusion and Discussions

In this paper, the conceptual scope of nuclear safety was investigated based on a preliminary survey in Korea after briefly reviewing the previous studies on safety [5, 6, 7]. Complementary safety concepts that can help improve the social acceptance of nuclear power were investigated based on surveys and interviews. Compared to the nuclear field, which is focusing on the development of new reactors such as SMR, the acceptance of the general public (*especially in Korea*) to nuclear power has not improved remarkably. This seems to reveal a fundamental difference in opinion on nuclear safety, which has traditionally pursued high reliability-based safety. Therefore, it is necessary to expand the conceptual scope of safety and develop specific scales, measures and standards for nuclear field in Korea in order to include more acceptable safety concept in especially the development and regulation of next-generation reactors.

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