【Research Note】

Risk Management and Decision-Making for Nuclear Safety: A Critique of Probabilistic Risk Assessment (PRA)※

原子力発電安全性におけるリスク・マネジメントと意思決定：確率論的リスク評価批判

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1. Introduction: Fukushima Nuclear Accident and Probabilistic Risk Assessments

There are two kinds of safety assessments or approaches to contribute to the decision-making for nuclear safety management: deterministic and probabilistic. According to the explanation of the International Nuclear Safety Group of the International Atomic Energy Agency (IAEA), the main elements of the deterministic are safety criteria, defense-in-depth and safety margins, while the ones of the probabilistic are comprehensive integrated analysis of potential accident scenarios and it can handle an

※ This research note is made on the presentation in 16th International Symposium on Public Sector Management held at Deutsche Universität für Verwaltungswissenschaften Speyer on July 5th, 2019.

unrestricted number of potential components failures and human errors. In other words, the former is a qualitative assessment of acceptable risk of undesired consequences, the latter is a quantitative assessment of risk from a broad spectrum on internal and external hazards (INSAG-IAEA 2011, p. 16).

Originally, the deterministic prevailed, but after the 1990s, the importance of the probabilistic has been identified, and now both the deterministic and the probabilistic are required to be integrated.

Certainly, the probabilistic, called PRA (probabilistic risk assessment) was more cost-efficient than the deterministic. A joint study of two institutes in the USA and Japan noted the cost-saving effect as follows: “the PRAs identified that many of the expensive backfits each plant was originally facing would have negligible impact on risk and identified low-cost modifications that had more significant risk impact. The PRA essentially saved the licensees hundreds of millions of dollars and improved risk (B. John Garrick Institute for the Risk Sciences and Nuclear Research Center 2017, p. 6).

At the same time, however, the PRA has been criticized as an indirect cause of the Fukushima Nuclear Accident on 11 March 2011. The accident, that is, explosions and meltdown of four reactors at the Fukushima Daiichi Nuclear Power Plant operated by the Tokyo Electric Power Company (TEPCO), had occurred by the stoppage of the cooling-water supply because the electric power for the water supply was cut off by the tsunami. The direct cause of the accident was that no improvements for protective measures had been made to prevent the loss of power under such conditions. The decision not to make improvements was affected by the PRA.

According to Ohmae, an MIT-trained nuclear engineer who is also widely regarded as Japan’s top management guru, the decision-making was based on two assumptions of the low probability of such an accident. The one assumption was that ‘the probability of long-term stoppage of external electric supply was so unlikely that we do not have to assume it might take place’. The other was that ‘the probability of a 15-meter tsunami hitting Japan is so low that you do not have to assume such a disaster because it is likely to take place once in 10,000,000 years’ (Ohmae 2012).

The government investigation report also criticized the applicability of PRA. “In that instance, when it deals with designing general machinery or buildings, the conventional approach of estimating the risk as “Risk = Probability of occurrence x Consequence of damage” will be applicable. However, in the government, as well as in private entities, a new approach to safety measures and emergency preparedness should be established for a disaster which potentially could bring about serious damage in a broad area like a gigantic tsunami or the severe accident at the Fukushima Nuclear Power Station, regardless of its probability of occurrence” (Investigation Committee 2012, p. 484).

In spite of those critiques, PRA is still made use of for the justification for reopening of reactors that have been shut down. For example, the probability of volcanic eruption could be too low (Japan Times 2019.).

Considering that situation about PRA, it is important to explore the nature and problems of PRA and to clarify whether the PRA could contribute to the perfect safety of nuclear plant operations. The exploring and clarifying will be made by investigating the development of U.S. NRC (Nuclear Regulatory Commission) documents.

This note is constituted in the following. Before describing the development of documents, the different definitions of risk and the peculiarity of the definition used under PRA will be noted. To the next point, the first report, named the Rasmussen Report, which introduced PRA in the field of nuclear safety assessment, will be examined. By publishing the 1995 statement of the NRC, PRA, along with the deterministic, became an important element of nuclear safety assessment, but, partly from a little before Fukushima, and decisively after Fukushima, criticism and questions about PRA have been increasing. That is the third part of this paper.

2. Definition of Risk and Uncertainty

(1) General definitions of risk by English dictionaries

Webster's Third New International Dictionary lists four meanings of risk: 1. The possibility of loss, injury, disadvantage, or disruption. 2. Someone or something that creates or suggests a hazard or adverse chance. 3. The chance of loss or the perils to the subject matter of insurance covered by a contract and 4. The product of the amount that may be lost and the probability of losing it.

From these, we can learn that risk is concerned with possibility, chance or probability. The first three definitions are also general meanings, to which other English dictionaries such as the Oxford English Dictionary (OED) also refer.

The definition we should specifically note is the fourth one: the product of the amount that may be lost and the probability of losing it. Risk is calculated as probability of occurrence multiplied by the consequence of damage. This is the special meaning of risk, which is examined in detail later.

Why is it noticeable and special? The answer for noticeability is because that definition was used in the first report which introduced the probabilistic method relating to nuclear safety: U.S. NRC (Nuclear Regulatory Commission) (1975). Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, WASH-1400 (NURG 75/014). The answer for specialty is because the application of risk made quantitative comparisons possible between different accidents and hazards and shows a lower risk of nuclear accidents.

(2) A distinction between risk and uncertainty by Frank Knight

Considering the distinction between risk and uncertainty made by American economist, Frank Knight, however, we should not be content with the definitions of risk. Knight pointed out in the book published in 1921, *Risk, Uncertainty and Profit,* that the term risk is loosely used, but that risk should be defined in relation to uncertainty. In

Chapter One, it is explained that proper risk is measurable uncertainty, while unmeasurable uncertainty is true uncertainty. In another chapter, a distinction between risk and uncertainty is not only one between measurable and unmeasurable, but also a distinction between objective and subjective probability. Moreover, he stated the following:

The practical difference between the two categories, risk and uncertainty, is that in the former the distribution of the outcome in a group of instances is known (either through calculation *a priori,* from statistics of past experience), while in the case of uncertainty this is not true, the reason being in general that it is impossible to form a group of instances, because the situation dealt with is in a high degree unique (Knight 1921, p. 233).

From this, it is understood that Knight saw the distinction between risk and uncertainty in the distinction between measurable and unmeasurable as well as between known and unknown.

Although Knight's distinction was not adopted by famous German sociologist, Niklas Luhmann (Luhmann 1991, p. 1), many researchers have supported and developed the distinction (in the research field of project management, see Saunders 2016). In his risk perception research, American psychologist, Paul Slovic, located 81 hazards on two factors of risk. The first factor dread risk or not, that is, uncontrollable or controllable. The second is unknown/unobservable or known/observable. Nuclear accident belongs to the category of dread and unknown risk. The second factor could be understood almost the same as Knight's distinction.

Does the risk in PRA have the same meaning as proper risk in the definition of Knight? If so, how would it deal with unmeasurable and/or unknown uncertainty? If it is not the case, another question arises. Could all risk or uncertainty, including unmeasurable and unknown, be dealt with in PRA?

3. Concept of PRA: Rasmussen Report and the Problems

(1) Content and characteristics of Rasmussen Report

The Rasmussen Report (U.S. NRC 1975) defined risk as consequence/unit time = Frequency (events/unit time) x Magnitude (consequences/event) like the above mentioned fourth definition by the Third Webster dictionary. Based on the definition, the report calculated the societal risk and average individual risk of death from auto accidents that occurred in 1971 as following:

In that year, there were about 150,000 auto accidents in the United States and one in 300 accidents resulted in a fatality. From these figures, societal risk is calculated as $15x10^6$ (accidents per year) x one death/300 accident = 50,000 death per year, and if the U.S. consists of 200,000,000 people, the average individual risk is expressed as probability of death, that is, 50,000 death per year/200,000,000 persons = $2.5x10^{-4}$. Similarly, the societal and individual risk of injuries and property damage in auto accidents are calculated.

On the ground of such a probability method, the report assessed the risks of nuclear accidents (mainly leading to the melting of the reactor core) and those of other man-made accidents as well as natural disasters. According to Table 1, the approximately individual risk of early fatality of nuclear accident (100 reactors) was calculated as $2x10^{-10}$, while those of motor vehicle accident, air travel accident, railway accident and hurricane damages were calculated as $3x10^{-4}$, $9x10^{-6}$, $4x10^{-6}$, $43x10^{-7}$ respectively (cf. Table 1).

Table 1. The 1969 fatality number and approximate risk in accident-type

Accicident Type	Total number for 1969	Approximate individual Risk Early fatality
Motor vehicle	55791	3×10^{-4}
Air travel	1778	9×10^{-6}
Railway	1148	4×10^{-6}
Hurricanes	90	4×10^{-7}
Nuclear Accident (100 reactors)	-	2×10^{-10}

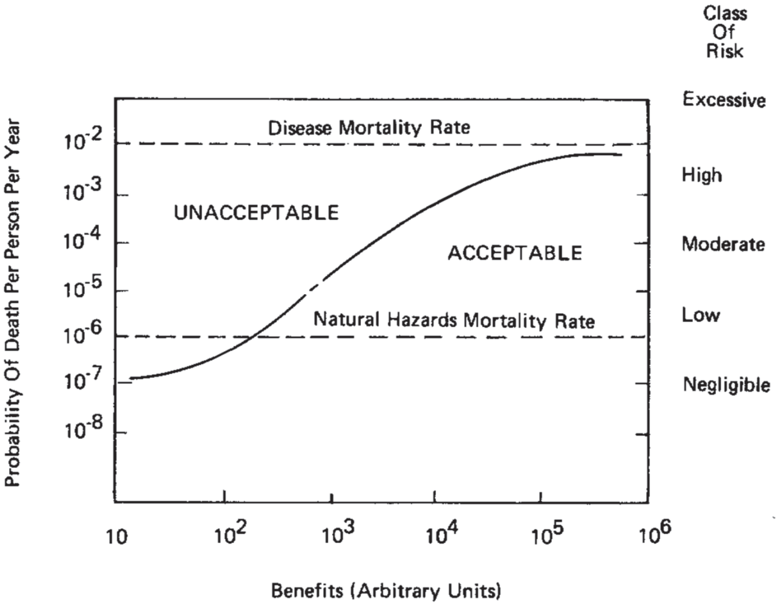
Source: U.S. NRC 1975, p. 112, selected.

From these calculations, the report concluded that “reactor risks are predicted to be smaller than many other man-made and natural risks” (U.S. NRC 1975, p. 132). The conclusion was not surprising considering the following proposition of the report on the public attitude toward accident probability: relation of acceptability for the risk and benefit by use of automobile or nuclear.

A death risk level per person per year of 10^{-3} “is generally unacceptable (to the public), and when it occurs, immediate action is taken to reduce it. / At an accidental risk level of 10^{-4}, people are less inclined to concerted action but are willing to spend money to reduce the hazard ” (U.S. NRC 1975, p. 11). “Risks of accidental death at a risk level of 10^{-5} per person per year are still recognized in an active sense. . . . and people accept” a certain amount of inconvenience to avoid risks, at this level. . . . Accidents with a probability of death of 10^{-6} or less per person per year are “apparently not of great concern to the average person” (U.S. NRC 1975, p. 11).

Adding the benefit to attitude towards accident probability, the range of acceptability could become larger (Figure 1).

Figure 1. A benefit-risk pattern



Source: U.S. NRC 1975, p. 17

(2) The problems of the Rasmussen Report

However, the conclusion on the probabilistic method should be criticized, especially on the following two points.

The first is concerned with the definition of risk as the product of frequency (events/unit time) and magnitude (consequences/event), which does not, as the report also admits, differentiate with respect to the magnitude of the consequences of accidents. The product of one accident per year and one death per accident is equal to the product of one accident divided by 10,000 years and 10,000 deaths per accident.

One should distinguish between big magnitude at low probability with small one at high probability. The report took this problem of risk aversion, as: “Society generally views the single large consequence event less favorably than the total of small events having the same average risk” (U.S. NRC 1975, p. 12), or “In general, single large accidents are viewed less tolerantly than multiple smaller accidents, even though the average annual consequences of the two are equal” (U.S. NRC 1975, p. 12).

As mentioned above, Slovic (1987) pointed out the importance of the distinction between the dread accidents and the not dread. The Rasmussen Report assessed risk magnitude only as death or injury. Slovic described the damages of nuclear accident which should not be confined to death, injury and to the amount of property damage, as the following:

> "Early theories equated the magnitude of impact to the number of people killed or injured, or to the amount of property damaged. However, the accident at the Three Mile Island (TMI) nuclear reactor in 1979 provides a dramatic demonstration that factors besides injury, death, and property damage impose serious costs. Despite the fact that not a single person died, and few if any latent cancer fatalities are expected, no other accident in our history has produced such costly societal impacts. The accident at TMI devastated the utility that owned and operated the plant. It also imposed enormous costs on the nuclear industry and on society, through stricter regulation (resulting in increased construction and operation costs) " (Slovic 1987, p. 283).

We, living after not only the nuclear accident at TMI in 1979, but also the ones at Chernobyl in 1986 and at Fukushima in 2011, have recognized the magnitude of the nuclear accidents.

Though all damages the Fukushima Nuclear Accident have brought are not yet entirely clear, its magnitude is shown from some figures. Many inhabitants had to be evacuated from a 30km radius around the plant. The evacuees numbered even now 42,929 as of May 2019 (Fukushima Prefecture Head Office for Disaster Control 2019). Compensations, which up to now have been paid, amounted to about 9 trillion yen. A fund needed for decommissioning and decontamination is estimated for each at 8 trillion. Consequently, the least estimated amount is expected to be about 22 trillion yen for so-called disposal and restoration (Committee for the Reform of Tokyo Electric Power Company and Fukushima Daiichi Nuclear Power Plant 2016) .

The second point in which we might criticize the Rasmussen Report is that it thought all risks are measurable, in other words, that unmeasurable risk, unknown risk by Slovic, or uncertainties by the terminology of Frank Knight, were omitted. Slovic used the term "unknown risk" in the meaning of such risk that is not observable, unknown to those exposed, with delayed effect, new and unknown to science.

4. Institutionalization of PRA in the U.S. Nuclear Regulatory Scheme as Complemental Instrument to the Deterministic

(1) Three Mile Island Accident and PRA

In spite of the above-mentioned criticism, Probabilistic Risk Assessment was supported and implemented by licensees (ex. Zion and Indian Point Plant in 1981 and 1982 respectively) and partly in certain areas by regulatory staff because of cost efficiency. In particular, after criticism of the Three Miles Island Nuclear Accident in 1979, the usefulness of PRA came to be identified because PRA had found a small LOCA (Loss of Cooler Accident) as a principal risk before the TMI accident (The B. John Garrick Institute for the Risk Sciences and Nuclear Research Center 2017, p. 9).

(2) PRA adopted as a formal regulatory assessment measure by the 1995 statement

PRA was finally adopted as a formal regulatory assessment measure by the 1995 NRC statement (U.S. NRC 1995). However, it did not mean that PRA replaced the NRC's traditional deterministic assessment measure as defense-in-depth. In fact, PRA was deemed to be complemental to the deterministic. That is represented by the following passage of the statement:

> "The use of PRA technology should be increased to the extent supported by the state-of-the-art in PRA methods and data and in a manner that complements NRC's deterministic approach . . .and supports the NRC's traditional defense-in-depth philosophy . . .PRA and associated analyses (e.g., sensitivity studies, uncertainty analyses and importance measures) should be used in regulatory matters . . .where practical within the bounds of state-of-the -art, to reduce unnecessary conservatism associated with current regulatory requirements, regulatory guides, license commitments, and staff practices." (requoted from U.S. NRC 2009, p. 1, original: U.S. NRC 1995, p. 8).

(3) PRA in the 1998 Integrated Risk-Informed Decision Making

In 1998, when regulatory guide 1.174 (U.S. NRC 1998) was issued, the NRC regulatory scheme came to be called Integrated Risk-Informed Decision-Making (IRIDM). Not to say, it is decision-making based on the integration of the deterministic and the probabilistic assessment measures. From the word "integration", one might think that the deterministic and the probabilistic (PRA) would have the same weight in decision-making. In reality, as of the 1995 statement (U.S. NRC 1995, p. 5), PRA was placed as complementary. The first and second points of 5 Principles of Risk - Informed Integrated Decision-making were stated as following: The first principle is that the proposed change meets the current regulations unless it is explicitly related to a requested exemption or rule change. The second is that the proposed change is consistent with the defense-in-depth philosophy (U.S. NRC 1998, p. 4).

At the same time, however, it is noteworthy that the U.S. NRC has identified the weak point of PRA: uncertainties.

5. Increasing Recognition of Uncertainties in PRA by U.S. NRC Statements

(1) 2009 guidance on the treatment of uncertainties

A 1995 NRC statement had evaluated positively the treatment of uncertainty by PRA as follows:

"The treatment of uncertainties is an important issue for regulatory decisions. Uncertainties exist . . . from knowledge limitation . . . . A probabilistic approach has exposed some of these limitations and provided a framework to assess their significance and assist in developing a strategy to accommodate them in the regulatory process" (U.S. NRC 1995, p. 6, also cited by U.S.NRC 2013, p. 1).

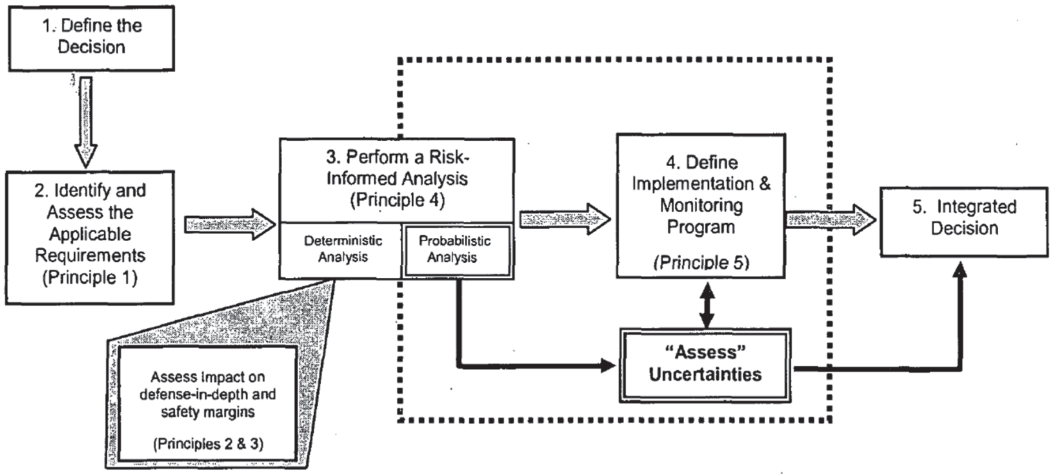
However, at the same time the statement added the passage: "The NRC staff must continue to develop new and improved PRA methods and regulatory decision-making tools" (U.S. NRC 1995, p. 8). It is without a doubt that one of the important issues for developing new and improved PRA was the treatment of uncertainties in the integrated decision-making.

Concerning that issue, the 2009 U.S. NRC main report titled "Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decision Making" stated two noteworthy points.

The first point is that the report classified more accurately the uncertainties in PRA and tried to make clear the limit for resolving uncertainties in the integrated decision-making.

According to the U.S. NRC Report: PRA is part of a risk informed analysis as illustrated in point three, Perform a Risk-Informed Analysis of IRIDM (Figure 2).

Figure 2. Elements of integrated risk-informed decision-making process



Source: U.S. NRC (2009), p.10.

The report classified uncertainties in two stages. The first distinction is drawn between aleatory uncertainty and epistemic uncertainty. The former is "associated with random nature of events" and such kind of uncertainties could be fully implemented by PRA. The latter epistemic uncertainties are categorized into three types of uncertainties: Completeness uncertainty, parameter uncertainty and model uncertainty (U.S. NRC 2009, p.13).

The completeness uncertainty, which is divided further in two categories: the known, but not included in the PRA model and the unknown. In order to deal with the known type of completeness uncertainty, conservative- and bounding-types of analyses could be used. For the unknown type of completeness uncertainty, other methods such as safety margins could be made use of (U.S. NRC, 2009, pp.15-16).

Parameter uncertainty, which relates to the uncertainty in the determination of the input parameter values to quantify the frequencies and probabilities of the events in the PRA logic model, could be dealt with risk calculations on the state-of-knowledge correlation (U.S. NRC 2009, pp.13-14, 31).

Model uncertainty relates to the uncertainty associated with some aspect of a PRA model that can be represented by any one of several different modeling approaches, none of which is clearly more correct than another. It could be addressed by making assumptions (U.S. NRC 2009, p. 14).

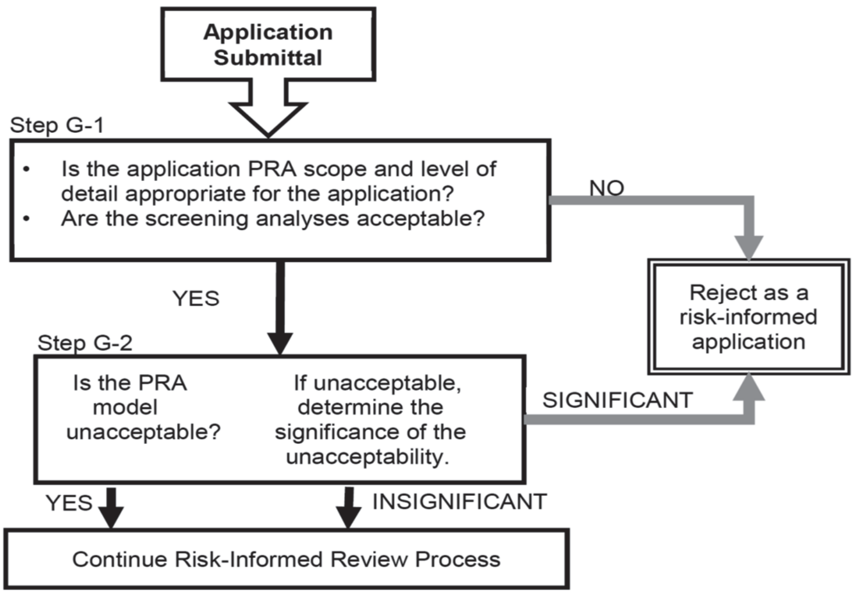
The main report, published in 2007, pointed out, as above mentioned, the parallel existence of three types of uncertainties and the necessary and alternative measures for correcting the uncertainties.

(2) Revised guidance after Fukushima

The second noteworthy point of the report is that it was two times revised (2013 as draft report for comment [U.S. NRC 2013] and 2017 as final report [U.S. NRC 2017]) and that finally the use of PRA might be more carefully checked in each stage of uncertainties.

In particular, with complete uncertainties, even if the application of PRA scope and level of detail would be appropriate for the application in the first step of the risk-informed review process, it is possible that PRA as a risk-informed application is rejected in the second stage, where the PRA model would be unacceptable, or the significance of the unacceptability would be determined (cf. Figure 3).

Figure 3. Overview of the risk-informed review of completeness uncertainty



Source: U.S. NRC (2017), p.127.

From the second point, one must recognize that reliabilities on the use of PRA in decision-making was less and less stable.

Behind that instability was the impact of Fukushima Daiichi reactor accident.

(3) Questions about PRA in the 2016 Report

PRA itself, in more accurate expression, the use of PRA in regulatory decision-making became the subject to be criticized. That can be understood from the fact that U.S. NRC had to publish the 2016 report, Probabilistic Risk Assessment and Regulatory Decision-making: Some Frequently Asked Questions. The report described the following:

> In 2011, following the Fukushima Dai-ichi reactor accidents, some critics raised concerns regarding the realism of the PRAs that provide the technical information needed in the NRC's risk-informed programs. Two principal complaints raised were (1) PRA-based estimates of the likelihood of major accidents were significantly smaller than simple statistical estimates based on international events (notably the accidents at Three Mile Island, Chernobyl, and Fukushima), and (2) PRAs did not predict the accident scenario experienced at Fukushima (U.S.NRC 2016, p. ix).

The report tried to tackle those questions by answering that the first question is oversimplified and the second is a reflection of a lack of understanding of the nature of PRA. In spite of further explanations, the report made the following conclusion:

> PRA models, as with any model, are imperfect representations of reality. Furthermore, unlike many models, PRA models also have to address the possibility of unlikely situations for which empirical data are (fortunately) sparse or even nonexistent. It is, therefore, important from a model validity viewpoint, as well as a broader safety viewpoint, to look for lessons from accidents and other significant operational events if and when such events occur (U.S.NRC 2016, p. 49).

6. Conclusion

From the hitherto analysis, it has become clear that the PRA was, at the first stage, adopted as an efficient and low-cost assessment method, then prevailed, however, in particular after Fukushima, it cannot remove uncertainties.

In other words, PRA is inappropriate as the means of decision-making concerning nuclear power plant safety. PRA could not realize the risk zero that should be needed in nuclear power plants because of accident severity. Of course, an alternative to PRA could be adopted, the deterministic assessment and measure, which could, in turn, lead to high cost. Therefore, the realistic alternative to risk-zero is the exit from nuclear power plants.

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