Nuclear safety in the unexpected second nuclear era

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Nuclear energy development has entered an unexpected second nuclear era, which is mainly driven by developing countries. Despite major efforts to pursue a safe nuclear energy system in the first nuclear era, severe nuclear accidents occurred. A basic problem is that we do not have an adequate understanding of nuclear safety. From the viewpoints of risk and the close coupling of technical and social factors, this paper reexamines the nature of nuclear safety and reviews how previous experts understood it. We also highlight the new challenges that we are likely to confront in the unexpected second nuclear era and clarify some of the refinements that need to be made to the concept of nuclear safety from a sociotechnical perspective. These include the following: 1) Risk decisions should be made based on integrating social and technical elements (i.e., "social rationality"); 2) risk needs to be controlled based on the "Wuli–Shili–Renli" framework; 3) systems thinking should be substituted for reductionism in risk assessment, and social mechanisms need to be combined to address uncertainties; and 4) public-centered risk communication should be established. This contribution can provide a theoretical foundation for improving our understanding of the nature of nuclear safety and for transforming the concept of nuclear safety in the unexpected second nuclear era.

nuclear safety | risk | sociotechnical perspective | unexpected second nuclear era

Since the 1950s, the exploitation and utilization of nuclear energy has had powerful effects on the development of human society and has greatly improved people's ability to understand and utilize the laws of nature. However, following decades of development, investment in nuclear power has begun to stagnate in many developed countries. In response to the Fukushima nuclear accident, some countries, such as Germany, Switzerland, and Belgium, have even decided to phase out nuclear power within the next 20 y. The share of global electricity contributed by nuclear power has fallen from 16 to 17% in the mid-1980s to ∼10% in 2018 (1). Meanwhile, the high cost of nuclear power and the public's doubts about its safety have led to dim prospects for the future development of nuclear energy, at least in much of the most industrialized parts of the world. According to a new International Atomic Energy Agency (IAEA) forecast of nuclear power development trends by 2050, nuclear power growth in developed regions such as Europe and North America is expected to be nearly zero, if not negative (2). Therefore, the second nuclear era (generally referred to the "nuclear energy renaissance") first proposed by Alvin M. Weinberg (3, 4), which was highly desired after the Three Mile Island (TMI) nuclear accident, has not yet appeared during the past 40 y, and today's reality is far from what Weinberg imagined.

Nuclear power construction in developed and developing countries has actually undergone a major reversal. Of the 55 nuclear power plants (NPPs) currently under construction, 47 are in developing countries (5). In addition, ∼28 countries without NPPs are planning or trying to launch nuclear power projects (6). Based on actual development trends in nuclear energy, we have redivided the eras of civilian nuclear energy as shown in Fig. 1, taking the Chernobyl nuclear accident as the approximate watershed. Our division is different from the concept of "the first and second nuclear eras" proposed by Weinberg in the 1980s (7, 8). In our definition, the first nuclear era, from the mid-1950s to the mid-1980s, was mainly led by developed countries (e.g., the United States, France, Japan, Germany, and the United Kingdom), where more than four times as many NPPs were built than in developing countries (e.g., the former Soviet Union and Korea). The development of NPPs in this era began with a short-term exploration, followed by a large-scale expansion. Primary drivers included nuclear weapons considerations (9), energy security (10, 11), and market factors (12), complemented by environment factors (13). Since the mid-1980s, the main force driving the development of nuclear power shifted to developing countries, and we call this"the unexpected second nuclear era." For large developing countries such as China and India, climate change and environmental pollution have become the main considerations for the development of nuclear power (11). For most of the newcomer countries enhancing energy independence and international influence through nuclear power is one of their important motivations (9), and concern about greenhouse gas emissions does not have a high priority in these countries because neither the Kyoto Protocol nor any other international agreement constrains their emissions. By contrast, developed countries are building few new reactors and focused on preserving existing plants and preparing for a possible bow wave of decommissioning at midcentury (14).

Compared with the first nuclear era, this unexpected second nuclear era exhibits some new realities. First is the impact of new suppliers on international nuclear safety governance. Nuclear suppliers from developing countries such as China, Korea, and India are entering market competition, while traditional leading suppliers (e.g., US-based Westinghouse and France's AREVA) decline. The emerging suppliers do not have a good record of

Significance

Despite great efforts to pursue a safe nuclear energy system during the first nuclear era, which was dominated by developed countries, severe nuclear accidents still occurred. Today, nuclear energy development has entered an unexpected second nuclear era, which is driven by developing countries. This may give rise to a great risk. Nuclear power plants are complex sociotechnical systems, and their safety has never been fully defined. We argue that social aspects, rather than just technical measures, must be involved to ensure nuclear safety. In this paper, the nature of nuclear safety is elucidated with identification of new challenges, and corresponding suggestions are proposed to improve nuclear safety in the unexpected second nuclear era.

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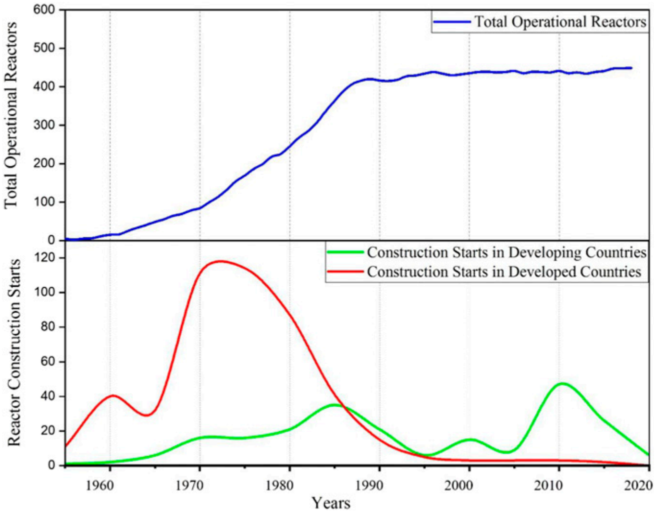

Fig. 1. Nuclear reactor construction starts and total operational reactors as a function of time (https:/pris.iaea.org/pris/). Data from the International Atomic Energy Agency.

recommending major improvements to the global nuclear safety governance system and are reluctant to take leadership in initiating improvements in the nuclear safety governance system. There are also concerns about the effective implementation of the existing nuclear safety governance system into these suppliers and some suppliers do not even participate in the international initiatives. Moreover, questions are also raised about whether the emerging suppliers will comply with international standards, and how that will affect importers and the global nuclear safety governance system (14). It is also not clear that the emerging suppliers will have the capacity to involve their regulators in helping recipient countries or will impose their domestic standards as a condition of supply. Second are challenges to domestic nuclear safety governance in nuclear newcomers. The construction of nuclear power is expanding into countries that previously lacked NPPs. This is especially the case in African and Asia–Pacific regions which lead in the new development of nuclear energy. These countries have relatively poor infrastructures, weaker rule of law and safety culture, less regulatory independence, lower scores on assessments of corruption resistance, and decreased nuclear technical and training depth (14, 15). Some regions are also stability-challenged, such as the Middle East. These factors give rise to a great deal of uncertainty with respect to nuclear safety. Third are new risks associated with technological evolution. Nuclear safety governance faces various threats different from those of the previous era, which are induced by technological evolutions: Cyber security issues are raised by extensive applications of digitalized instrument and control systems (16), escalating into plant safety threats by inducing wrong operator actions, and advanced reactors favored by newcomers, which are smaller and expected to be more widely distributed than existing NPPs, may place an additional strain on the existing governance system [e.g., terrorist threats on floating small modular reactors (17)]. In addition, many older nuclear reactors are reaching their design lifetimes, with nearly 100 reactors operated for 40 y or more. Lifetime extensions or decommissioning of many old reactors would pose safety issues like decreased safety margin and radioactive wastes.

The growth of nuclear energy in developing countries in recent years has sparked a widespread discussion (18–20). Although nuclear energy is considered to be important for meeting energy demands and fighting climate change, the spread of nuclear power in developing countries is also accompanied by great risks, which have already presented challenges in nations with well-developed nuclear infrastructure, as seen in the Fukushima nuclear accident in Japan. NPPs are complex sociotechnical systems that face threats to safety caused by system complexity, personnel unreliability, and technical limitations. Plant safety depends on comprehensive risk management, including advanced technology research and development, operations management, and government supervision. However, the industrial level in developing countries is currently much lower than that of developed countries. In addition, as exemplified by the recent vaccine scandal in China and food safety scandal in India, developing countries' laws and regulations, talent pools, and supervision and emergency response mechanisms are not yet sound. Even worse, nuclear power is not a publicly accepted choice in some developing countries; instead, it is merely wishful thinking of governments hoping to increase their countries' international prestige. This situation could lead to protests similar to the Indonesian public's antinuclear parade. Hence, all these factors inevitably increase worry about nuclear safety in the unexpected second nuclear era.

Despite great efforts to improve nuclear safety and the development of a series of safety theories, methods, and measures proposed in the first nuclear era, severe nuclear accidents have occurred. Lessons learned from the nuclear disasters are generally divided into two categories: those that blame technical factors (such as reactor design defects and inadequate risk assessment models) and those that blame social factors (such as human/organizational errors and poor regulations). Social factors have drawn more and more attention (21) in the unexpected second nuclear era, owing to the fact that technical factors are not dominant with the continuous development of NPP technologies and the accumulation of operating experience. In fact, the social and technical factors cannot be treated separately, because NPPs are complex sociotechnical systems, and we actually have no adequate comprehensive understanding of nuclear safety. In this paper, we have reviewed the history of nuclear safety research and rethought the nature of nuclear safety. We propose that technical and social factors should be closely linked to address the nuclear risk. This contribution provides a theoretical foundation upon which to continuously improve nuclear safety in the unexpected second nuclear era.

The Nature of Nuclear Safety

Nuclear safety research started with the Fermi reactor, where multiple redundant safety systems played important roles in keeping the whole operation under control. However, in the unexpected second nuclear era, the concept of nuclear safety has gone far beyond technology, as nuclear safety has been recognized as a prevalent social issue more than a technical issue (22). According to the fundamental safety principles in the safety standards of the IAEA (23), nuclear safety entails "the protection of people and the environment against radiation risks, and the safety of facilities and activities that give rise to radiation risks." This definition explains nuclear safety through "safety" and "risk" but does not clarify the nature of nuclear safety. Although it addresses the goals and radiation-related aspects of nuclear safety, it does not touch on nuclear safety beyond radiation (i.e., the close coupling of technical factors and social factors as well as their comprehensive impacts on safety).

Before investigating the nature of nuclear safety, we need to understand what safety is. However, safety is a multidisciplinary concept, and there is no consensus on its definition despite the large number of studies on the subject. Safety is defined as a type of status, ability, process, condition, and so on. We find that regardless of how safety is defined, its interpretation inevitably involves risk. According to ISO 31000, risk is the "impact/effect of uncertainty on objectives" (24), whose definition based on uncertainty is adopted in this paper. The objectives here refer to something that humans value (including humans themselves, environment, money, etc.) involving physical and mental aspects.

Thus, the nature of safety can be understood as the ability to cope with uncertainties and their adverse impacts/effects on humans both physically and psychologically.

The uncertainties in nuclear safety come from the social and technical aspects of the system and their interrelatedness. Compared with systems in other industries, the features of nuclear energy systems are embodied in the principles of nuclear fission reactions. A fission chain reaction is the prerequisite for nuclear power, but it also creates the potential instability of nuclear power. First, there is a likelihood of prompt supercriticality that can lead to drastic power increasing within a very short time, which may ultimately result in severe core damage and even collapse. Second, decay heat is still generated after shutdown (25) and may cause core meltdown if not removed effectively. Third, many radioactive fission products, including fission fragments and their decay products, are produced, some of which have very long half-lives. Once these fission products are released into the environment in severe accidents, they can pose a great threat to human life and health. For example, the TMI nuclear accident was caused by the failure of technical components compounded by operators' incorrect judgment. In the Chernobyl nuclear disaster, a combination of reactor design flaws and operation contrary to the checklist of safety tests eventually resulted in the large release of radioactive materials into the environment.

An accident induced by uncertainties in the nuclear energy system may be a serious threat to humans and the environment, and these uncertainties cannot be fully eliminated by technical approaches. Thus, social mechanisms should be used to cope with uncertainties. Nuclear accidents may bring about multiple special impacts compared with accidents in other industries. First, there will be health effects from radiation (fatalities, cancers, hereditary effects, etc.). Second, radioactivity, which is invisible and untouchable, leads to extensive psychological fear. Third, the impact is large and lasts for a long time after a single accident (26–28). For instance, in the Fukushima nuclear accident, there were no prompt fatalities, and no discernible cancer effect was expected to occur. However, people experienced lasting psychological trauma, and there were major impacts on the environment, economy, and politics. The cleanup remains difficult, and the recovery costs are huge even after the accident.

In summary, multiple social and technical measures, including advanced design concepts, operations management, safety regulations, and safety culture, should be integrated to address the uncertainties of nuclear energy systems and to control their risks. Meanwhile, different methods, including probabilistic risk assessment (PRA), should be applied to evaluate the potential physical and psychological hazards. In addition, it is worth pointing out that technical and social elements are closely coupled in nuclear safety. Technical aspects, such as risk models and safety principles, have been embedded in social value and practice. Meanwhile, the social aspects (e.g., safety culture, safety regulation, and public acceptance) have also been reflected in the operation of NPPs. Nuclear power cannot successfully develop without risk communication, and decision making for acceptable risk should also be performed with sufficient public participation to improve public acceptance of nuclear energy. As shown in Fig. 2, social mechanisms and technical approaches should be synthesized to cope with the uncertainties resulting from technical and social elements and their interaction in the system.

Social Rationality-Based Risk Decision Making

A fundamental question in managing hazardous technologies is, "how safe is safe enough?" This is a catchy phrase used to identify the acceptable risk of a certain activity or product (29). To answer this question, in the early days, minimum requirements, including a series of rules and guides based on defense in depth (DiD), as low as reasonably achievable, and safety margin principles, were established for how NPPs should be designed, built, and operated, but without specifying the safety level that they were hoping to achieve. This question was not addressed directly until safety goals were adopted in the nuclear industry (30).

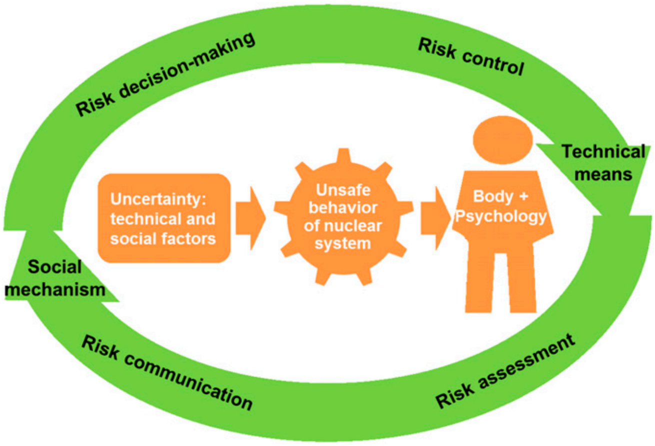

Fig. 2. Nuclear safety based on the close coupling of society and technologies.

The Evolution of Acceptable Risk. Two academic papers brought the acceptable risk of NPPs to the forefront of nuclear engineering in the late 1960s. The first one was published in 1967 by F. R. Farmer, entitled "Reactor safety and siting: A proposed risk criterion," in which he first linked the acceptable accident frequency to the release of radioactive materials to form a set of quantitative safety criteria (31). The second paper was published in 1969 by C. Starr in *Science* and was entitled "Social benefit versus technological risk," in which he offered an approach to establish the "acceptable risk" for NPPs based on historical data and pointed out that "the public is willing to accept 'voluntary' risk roughly 1000 times greater than 'involuntary' risk" (32). By 1975, the application of PRA in the Reactor Safety Study (WASH-1400) made it possible to set quantitative safety goals. However, the regulatory authority did not take the concept and value of quantitative safety goals seriously until the TMI nuclear accident in 1979.

During the investigation of the TMI accident, the US nuclear community, including the Nuclear Regulatory Commission (NRC), began to recognize the necessity of safety goals; then, the two "0.1%" quantitative health objectives (QHOs) were proposed by the NRC after years of work. That is, for an individual near a NPP (within 1 mile), prompt fatality risk should not exceed 0.1% of the sum resulting from other accidents, and for the population near the site (within 10 miles), cancer fatality risk should not exceed 0.1% of the sum resulting from other causes. The probabilistic safety criteria and safety goals at the technical level were first developed by the United States to substitute for QHOs in practical use, which generally refer to the frequency of core damage (CDF) and the release frequency of large amounts of radioactive materials (LRF/LERF). The probabilistic safety criteria have been widely recognized and applied in nuclear safety regulation around the world. There are three categories regarding the status of probabilistic safety goals (33): 1) a legally strict value to be fulfilled, 2) a strict value that is not legally binding, and 3) a target value used as one piece of information in the risk-informed regulation. However, practically, there is a consensus for new plants, where not meeting the probabilistic risk criteria would prevent the regulatory body from granting an operating license. Analysis of the reasons for exceeding the target values will be required to identify the cause, and compensatory actions must be taken to correct the cause. Therefore, probabilistic safety goals (especially CDF) have in fact become regulatory limits. Meanwhile, to improve safety, the criteria for new NPPs are generally 1 order of magnitude higher than those for existing NPPs (Table 1). For some countries such as France, probabilistic safety goals are not espoused considering that these could lead to a low motivation for supplementary safety improvements, even if an improvement could be carried out at a low cost (34). However, the Fukushima nuclear accident reminded us to reexamine the rationality of our current safety goals. In terms of radiation health effects, there were no prompt fatalities, and no discernible cancer effect is expected to occur owing to the timely evacuation of the public. Thus, the Fukushima power plant still meets the two "0.1%" safety goals, leading to the conclusion that its safety level should be acceptable even considering the great impacts of the nuclear accident on the environment, economics, and politics. Obviously, the public does not accept this conclusion. In addition, the rationality and credibility of using these two probabilistic safety criteria (CDF and LERF/LRF) to indicate the safety level of NPPs has aroused broad skepticism because three major nuclear accidents have already occurred since 1979.

In fact, there are different philosophies in the world with respect to safety goals. The United States focuses on mortality and direct monetary costs of on- or off-site consequences, and cost benefit analysis aspects are important (e.g., the monetary value of human life estimated up to several million US dollars). In contrast, in the European Union, a stringent safety goal implying the "practical" prohibition of large-scale evacuation and land contamination subsequent to an accident has been proposed for the fear of accidents, especially of severe accidents. To restore public confidence in nuclear energy, the safety goal of "practically eliminating the possibility of large releases of radioactive materials,"

Table 1. Probabilistic safety goals of main countries and organizations

Countries/ organizations	CDF*		LRF/LERF†	
	Definition	Value	Definition	Value
IAEA	Likelihood that an accident could cause the fuel in the reactor to be damaged	10^{-4} (objective, old plant) 10^{-5} (objective, new plant)	As absolute quantities (in becquerels) of the most significant radionuclides released, or as a fraction of the inventory of the core, or as a specified dose to the most exposed person off the site, or as a release resulting in "unacceptable consequences"	10^{-5} (objective, old plant) 10^{-6} (objective, new plant)
United States	Llikelihood that an accident could cause the fuel in the reactor to be damaged	10^{-4} (objective, old plant) 10^{-4} (objective, new plant)	Frequency of those accidents leading to significant, unmitigated releases from containment in a time frame before effective evacuation of the close-in population such that there is a potential for early health effects	10^{-5} (objective, old plant) 10^{-6} (objective, new plant)
China	Likelihood that an accident could cause the fuel in the reactor to be damaged	10^{-4} (objective, old plant) 10^{-5} (objective, new plant)	Releases resulting in off-site emergency	10^{-5} (objective, old plant) 10^{-6} (objective, new plant)
Japan	A benchmark for the performance of safety functions for preventing severe accidents	10^{-4} (objective, old plant)	Containment failure (CFF‡)	10^{-5} (objective, old plant)
Korea	For PWRs: maximum fuel cladding temperature >2,200 °F (1,204 °C), or uncovering of top of the reactor core except cases caused by instant reflooding. For PHWRs: multiple fuel channel failure	10^{-4} (objective, old plant) 10^{-5} (objective, new plant)	Rapid, unmitigated large release of airborne fission products from containment to the environment, resulting in the early death of more than 1 person or causing severe social effects	10^{-5} (objective, old plant) 10^{-6} (objective, new plant)
Finland	1,204 °C corresponds to failed core cooling which leads to a fuel cladding failure	10^{-5} (objective, old plant)	100 TBq ^{137}Cs	5×10^{-7} (limit, old plant)
Sweden	Local fuel temperature above 1,204 °C	10^{-5} (objective, new plant)	0.1% of core inventory	10^{-7} (objective, new plant)
Canada	Failure of more than one fuel channel (CANDU)	10^{-4} (objective, old plant) 10^{-5} (objective, new plant)	100 TBq ^{137}Cs	10^{-5} (objective, old plant) 10^{-6} (objective, new plant)

*The CDF criterion is considered as based on defense-in-depth and seeks to prevent the safety design of a plant from relying too much on containment; it can also provide measures used by different countries, thus allowing comparisons of safety.

†LRF/LERF is based on protecting the public against prompt fatalities and radiologically induced cancers (LERF criterion is based on the time being sufficient for public evacuation before a significant release occurs).

‡The CFF gives more conservative assessment when the same value is taken for CFF and LERF, and it is a way to cope with the uncertainties in the quantification of source terms and the effectiveness of emergency protective measures and so on.

which was proposed by the European Union and later endorsed by the IAEA, has received much attention worldwide (35). The elimination of off-site evacuation has become a general requirement for Gen-IV reactors and fusion power plants (36). However, to ensure that these safety goals are more effective, it is very promising to achieve the physical elimination of these situations rather than only probabilistic elimination, yet the former remains a huge challenge.

Decision Making for Acceptable Risk Based on Social Rationality. To answer the question, how safe is safe enough?, we need to return to the origin of the question that establishing safety goals is a social issue, not just a technical issue. It is essentially a form of decision making for acceptable risk (37) and requires the full participation of all parties concerned to find a balance among nuclear safety, economy, and public acceptance. However, nuclear safety goals are traditionally determined by the "experts" at regulatory authorities and nuclear enterprises, who make decisions by calculating and comparing the benefits and the expected loss of nuclear energy with those of other fields. These experts saw this technology-based approach as absolutely rational, and according to them, if the safety goals cannot be understood and accepted by the public, there must be something wrong with the public. However, experts are also boundedly rational; they are still influenced by their values, experiences, and social relations, and they are limited by their specialties: Their likelihood of making errors may be higher than that of the public. The decision-making process cannot be guaranteed to be objective and unbiased. Therefore, we proposed that for safety regulation in the unexpected second nuclear era, the idea of social rationality, which holds that every individual is boundedly rational but each has its own merits, should be integrated in decision making to coordinate technical and social viewpoints representing all walks of life (38) so that the established safety goals are widely understood and accepted (Fig. 3).

Values are important factors that affect the risk decision making of all stakeholders. Nuclear industries are concerned about how to maximize benefits while achieving safety goals, whereas the public is more concerned about the potential losses caused by nuclear accidents (Fig. 3). This situation requires consensus on what types of criteria should be used to evaluate the consequences of a nuclear accident. Nuclear accidents would have serious impacts on aspects of physical and mental health as well as on the environment and economy (39, 40). However, differences exist in public perceptions and acceptance of multidimensional risks. Therefore, a broad survey of public opinion needs to be performed to identify the diversity of their needs. Actions including proactive steps to motivate all stakeholders, open and transparent information sharing, and trying to satisfy multiple interest positions (41) should be enhanced to promote the public participation in the risk decision-making process. Meanwhile, to support the assessment of different impacts of accidents and ascertain the additional risk induced into total societal risk, future studies should be required to examine low-dose radiation effects (42), the migration of radionuclides in the environment (43), and psychological trauma assessment (44).

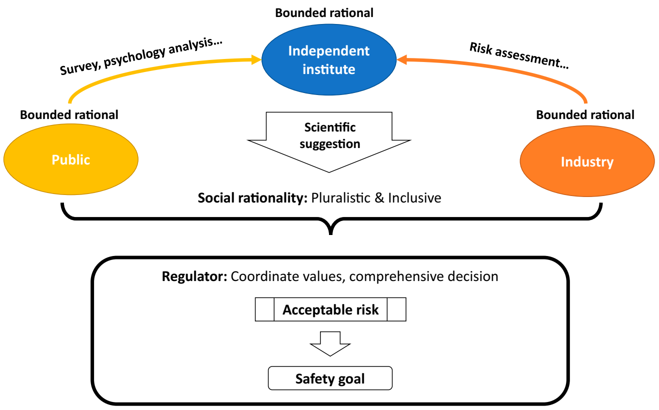

Fig. 3. Decision making for acceptable risk and values integration. Note: Various values should be integrated according to the principles of social development, industry characteristics, ethics and utility. Public values are mainly impacted by the public's political and cultural background, potential losses, information acquisition, voluntary participation, and alternative options. Industry values are impacted by the industry's political and cultural background, regulation requirements, accident characteristics, risk controllability and plant economics, and so on. Independent institute's suggestions are based on current knowledge, NPP features, social impacts, and so on.

Wuli–Shili–Renli-Based Risk Control

After identifying the acceptable risk level of NPPs, how best to control risk through design and management is naturally the next issue to be analyzed.

The Evolution of Risk Control. In the early stages of nuclear energy, nuclear reactors were built far away from where crowds might congregate to avoid impacts on the public. As nuclear power was commercialized (45), containment—considered to be infallible at that time—was designed by the nuclear community with the goal of containing radioactivity. However, the working group of the Atomic Energy Commission (AEC) noted in 1967 that a loss of coolant accident could cause a containment breach if the emergency core cooling system failed to operate (46). Then, a large amount of research was deployed on engineered safety features to reduce the probability and mitigate the consequences of core melting accidents. In the same year, the AEC proposed the concept of DiD, including three levels: prevention, protection, and mitigation. Hereafter, the possibility of severe accidents was demonstrated by the TMI accident, and severe accident management guidelines were developed to address beyond-design-basis accidents. Then, the Chernobyl accident confirmed the importance of off-site emergency planning (47). In 1999, the concept of DiD was regarded as a fundamental safety principle by the IAEA, which had formulated a construct comprising five different levels of defense and four physical barriers (48). The design requirements for DiD are derived by repeated application of the question, What if this barrier or safety feature fails? In the United States, the results of that process are documented in the regulations themselves, specifically in Title 10, Code of Federal Regulations, as the "prescriptive" requirements (49). The concept of DiD has matured, with much commonality in its understanding and application among nuclear industries around the world. For example, there were different constructions for NRC and IAEA, but they shared a logical consistency (50). In the Fukushima accident, all measurements to remove residual heat from the core failed due to a tsunami triggered by an earthquake, which eventually led to a large release of radioactive materials into the environment. Afterward, further considerations about the extreme external hazards were proposed for inclusion in DiD. In response to the question of how to control risk, the trend in research has been shifted away from "safety relying on remote locations and containments" to "reducing the probability and mitigating the consequence of accidents through redundant design and engineered safety features." DiD as a fundamental safety principle has been gradually established. The implementation of DiD in some countries, such as the United States, China, The Netherlands, Mexico, and India, started moving toward a risk-informed and performance-based (RIPB) (50, 51) approach from a prescriptive one (49). The RIPB concept was developed in an attempt to answer the questions of whereDiD is needed and how much DiD is adequate (52). Accordingly, passive-safe and fail-safe principles have been applied to enhance the safety critical systems of DiD (53), such as the passive decay heat removal system in AP1000. Based on the review above, we found that in the past there was still a lack of comprehensive thinking about nuclear safety design and management, and the approach of the past could not effectively integrate social and technical elements to reduce the adverse effect of uncertainty on safety. Currently, risk control focuses too much on the impact of technical factors on system safety and pays insufficient attention to social and technical interactions. On the one hand, the implementation of DiD increases system complexity (50, 54). However, the safety of complex systems is increasingly subject to human and organizational factors (55). This issue has not been effectively addressed by human reliability assessment (HRA) techniques (54, 56). On the other hand, as Reason pointed out, system operators and managers may be left blind to the increasingly degraded state of a system, and they may not recognize the degradation early enough if it is obscured by successive lines of DiD (57). This information asymmetry will shorten the intervening time window, which may lead to severe consequences (58, 59).

In summary, in sociotechnical systems such as NPPs, risk control fundamentally relies on the comprehensive effect of social factors, technical factors, and their interaction. Therefore, nuclear safety should be achieved through these three original aspects (60).

Wuli–Shili–Renli-Based Thought Achieves Reasonable Control of Nuclear Risk. Wuli–Shili–Renli (60), originally proposed to manage sociotechnical systems, is adopted to control nuclear risk to address social and technical elements in a theoretically informed and systematic way (Fig. 4).

Wuli. Although human factors and information symmetry are very important for safety achievement, disruptive improvement in nuclear safety may be more likely to arise from technological innovations. For example, DiD ensures the safety of nuclear reactors mainly by additional safety measures. Relatively speaking, innovative reactor designs, seeking a breakthrough from physical technology and eliminating potential hazards from the source, are important orientations for nuclear safety development. To ensure nuclear safety from the origin, research focus has shifted from "relying on complex design and engineered safety features" to "improving the design of the reactor itself" and hence reducing the impact of uncertainty on DiD. For example, these features include minimizing the production of radioactive materials, achieving self-control of reactivity based on negative feedback, and substituting water with inherently safe coolant, which is chemically inert and can be operated under normal or low pressure.

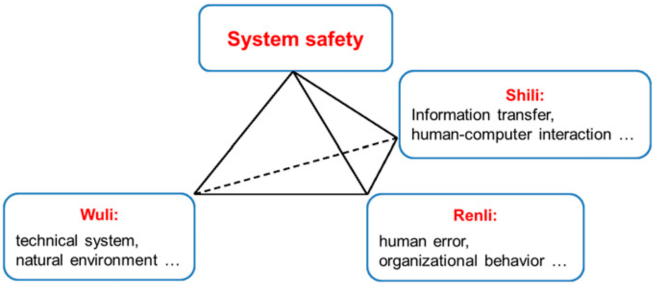

Fig. 4. Comprehensive effect of Wuli–Shili–Renli on safety. Note: Wuli–Shili–Renli philosophy is a Chinese expression for an integrated framework of systems thinking, which consists of 3D aspects in a sociotechnical system: social factors (Renli), technical factors (Wuli), and social and technical interactions (Shili).

Shili. Accidents generally result from a breakdown in the flow and interpretation of information, and all of the accident factors, such as states of technical systems, human, energy, culture, and management can be represented by information (61). For the acquisition and utilization of safety-critical information, many novel safety models and methods have been proposed. For example, a novel safety principle termed "observability-in-depth" (OiD) is proposed as a supplement to traditional DiD. The core idea is as follows: A set of technical, operational, and organizational provisions are designed to enable the monitoring and identification of emerging hazardous conditions and accident pathogens in real time and over different time scales. OiD also requires monitoring the conditions of all confinement barriers that implement DiD (62). OiD not only improves the traditional DiD principle but is also of great significance to the implementation of online risk monitoring in the future (59). Of course, the successful deployment of OiD relies on further developing types of sensors adapted to rigid environments, such as high temperature, high pressure, and high radiation. Collection and analysis techniques that can be applied to huge amounts of data should be studied, such as artificial intelligence (AI) (63) and big data (64). In addition, OiD currently considers only the information transferred from technical systems to humans, and we need more research on the interactions among human and between human and technical systems, such as information-based accident analysis and preventing measures.

Renli. Human and organizational performance in normal operations and accident management have to be improved to better address the uncertainty of plant conditions. Resilience theory, which has been widely recognized in recent years, represents a new way of thinking about safety. Resilience theory advocates enhancing the emergent property generated in a recursive management process of an engineering system to cope with the threats to safety induced by real-world complexity and to respond to and recover from some unexpected external events at early stages, by minimizing their impacts on the stability of systems (65, 66). Resilient perspectives focus on how individuals and organizations adjust their performance to unexpected events when DiD is challenged. Unlike most HRA methods that aim to predict the performance of an "average crew," resilience engineering pays more attention to the differences in the activities of crews on a microlevel (67) and the specific interactions among operators, teams, resources, technology, and the circumstances of the scenario (68, 69). Accordingly, it is an important move from improving system reliability to emphasizing system resilience in the risk management of complex systems. Resilience engineering can be a strong complement of risk analysis. To achieve safety by improving human and organizational performances, the combination of DiD, safety culture, and resilience engineering should be enhanced alongside deep research on the theoretical and ethical aspects of resilience. Additionally, future studies should focus on the quantitative methodology for precisely estimating the resilience level of sociotechnical systems. More case studies should be carried out to accumulate staff and organizational data on nuclear design, operation, and so on, especially at the managerial and institutional levels.

Technical Humility-Based Risk Assessment

The basic idea in determining reactor safety is that if a nuclear reactor can demonstrably meet acceptable risk level and maintain a sufficient safety margin under the disturbance of uncertain events, the reactor is deemed safe (70). Furthermore, building an NPP is only permitted when approved by regulatory authorities.

The Evolution of Risk Assessment. In risk assessment, accidents have been considered from the perspective of a specific event to that of more comprehensive initiating events, and the evaluation method was developed from a deterministic method into a probabilistic or hybrid method. In the early stages, risk assessment for NPPs was based on the concept of a "maximum credible accident" (MCA), a specific accident with a potentially hypothetical hazard that cannot be exceeded by any other supposedly credible accident during the lifespan of a reactor (71). However, demonstrating reactor safety based on MCA was inadequate due to great uncertainties in the selection of this accident. MCA was later replaced by a set of postulated accidents, which were design basis accidents (DBAs). Accidents with severity beyond that of DBAs were thought to be incredible. Therefore, if a plant could handle DBAs, its safety was considered to be sufficiently proven. So-called deterministic safety analysis was gradually developed, in which a single failure criterion or operational experiences were applied in the selection of DBAs, and the effectiveness of physical barriers and safety systems was evaluated by conservative assumptions (70).

Before the TMI accident, the Reactor Safety Study (WASH-1400 in 1975) based on PRA showed that the realistic threats to the public were mainly from core melting accidents. Instead of receiving sufficient attention, this study became subject to major doubt (72). The TMI accident showed that multiple failures may cause core melting accidents much worse than those of DBAs, which confirmed the finding of WASH-1400 and directed much attention to the application of PRA. Hence, the WASH-1400 became a major milestone in the history of probabilistic methods (70). Decision makers began to focus on the negative insights provided by PRA (73), that is to say, some new system faults were revealed. Later, with ongoing application of PRA, decision makers began to pay greater attention to its positive insights (i.e., that some overly conservative requirements could be relaxed).

In recent years, PRA has gained wide application in many countries. According to the way that countries have approached the development of the PRA standards and guidance, PRA can be mainly divided into four broad categories (34): 1) National standards and guidance have been or are being developed (e.g., the United States and India); 2) high-level requirements and guidance are defined by the regulatory body (e.g., the United Kingdom and Korea); 3) no specific national standards or guidance have been defined and the methods used have been developed by the utilities and accepted by the regulatory body (e.g., France and Sweden); and 4) no specific standards or guidance have been developed with a high reliance on what has been produced elsewhere (e.g., Italy). Despite the use of PRA by a licensee has been not a legal requirement in some countries, it still plays an important role in the safety improvement of NPPs. This is the case in France, where the fleet of operating reactors is highly standardized and its assessment is based essentially on a deterministic approach and PRA is not required by the safety authority. However, the utilities have developed their own methods and guidance, and this has led to important improvements in the quality of the PRA.

It should be noted that current deterministic assessment and PRA tend to overemphasize technical systems with a strong belief that if the technologies work the plant is safe. Moreover, these methodologies are mainly based on reductionism, which breaks the system down into smaller parts to make it manageable. However, working with each aspect separately cannot reflect the dynamic interactions of system elements and cannot give the full picture of the system. Therefore, existing risk assessment theories for NPPs need the breakthrough of a new methodology.

Technical Humility-Based Risk Assessment. A risk assessment methodology based on technical humility is proposed with coupling of systems thinking and social mechanisms. Systems thinking views safety as an emergent property and analyzes the dynamic and interactive characteristics in a system's evolution, as well as the coupling relationships between social and technical factors, to provide a full picture of the system. Therefore, the risk assessment of NPPs should shift its approach from reductionism to systems thinking in the future. However, the existing risk assessment techniques based on systems thinking still face great challenges, and even systems science itself needs improvements at the theoretical level (74). It is our opinion that at the current stage we can use dynamic reliability methods developed on the basis of probabilistic dynamics theory and discrete dynamic event trees to model and analyze systems with regard to their dynamic characteristics. Dynamic reliability techniques are relatively mature and have been applied to the dynamic PRA of subsystems of NPPs. Improvements in size limits and calculation speed should be made to meet the requirements of plant-scale applications in the future (75, 76). Regarding interactive features, we may refer to the Systems-Theoretical Accident Model and Process, the Risk Management Framework of Jens Rasmussen (56, 77–79), and so on. However, these approaches are only qualitative frameworks and cannot carry out quantitative analysis and application (80, 81). Holism and reductionism need to be further integrated: Interactions reflect holism, and reductionism embodies technical solvability. The key point is to determine the balance between holism and reductionism. The major development trend in nuclear risk assessment in the future for systems methods will be deeply integrated with AI (63, 82–87), big data (88), dynamic uncertain causality graphs (89), and other new technologies, with the goal of predicting the faults of complex systems.

However, due to the inherent limitations of human cognition, uncertainty always exists in theories, methods, and techniques. Hence, we should know when to direct our attention to solutions beyond risk assessment techniques, that is to say, to social mechanisms. From a social perspective, we should treat risk assessment correctly and respect the public's open and fair comments on the different risk assessment models (including terminologies, assumptions, and results) instead of neglecting them in the inaccessible computer codes and hidden discussions of experts. Technical humility herein refers to methods, or better yet an institutionalized thinking habit, that try to come to perceiving the ragged fringes of human understanding—the uncertain, the unknown, the uncontrollable, and the controllable (90). Technical humility recognizes the insufficiencies of risk assessment, and we should turn from technical optimism to humble practice and devote enough efforts to designing social mechanisms to address uncertainty which requires different expert knowledge and different forms of participation between decision makers, experts, and the public that are considered needful in the governance structures of high modernity (91). In the face of uncertainty, building the capacity of risk management must be a multidisciplinary activity that involves psychology, management science, political theory, and so on in addition to risk assessment.

Risk Communication Based on Objective and Subjective Risk

The purpose of developing NPPs is ultimately to serve the public. Unfortunately, public skepticism of nuclear power, heightened by the three major nuclear accidents, has hindered the development of nuclear power. Accordingly, risk communication has become an indispensable task for the nuclear industry.

The Evolution of Risk Communication. In the early days, the development of nuclear energy was mostly related to the will of countries, and nuclear reactors were built far away from where crowds might congregate. At that time, the public had little knowledge of nuclear power and no strong desire to learn about it (92). Therefore, public communication was either unnecessary or just a prior work for nuclear power projects. Only when the TMI accident eroded the public's faith in nuclear power was public communication finally taken seriously, but it was only used to familiarize the public with nuclear technology to make them accept it (93). Therefore, the function of public communication was one-way: informing, persuading, and educating the public at that time. It was difficult to establish real trust because the two sides of the communication were unequal in status.

This one-way communication overemphasized the dissemination of objective risk, such as science popularization, while ignoring the subjective risk. Note that the objective risk here refers to risk measurement by experts and the subjective risk denotes perceived risk of the public. People often rely on their intuition to perceive and judge risks in real life, which results in a great difference between objective risk and subjective risk. In addition, false information and fake news also have impacts on public perception of risk. For example, some media exaggerated the consequences of nuclear accidents, while some nuclear industries overstated the safety of nuclear energy. In the latter case, the uncertain results of risk assessment were generally propagated as determined results, such as that a nuclear accident would happen only once in a million years. However, the Fukushima nuclear accident revealed fragile public acceptance of nuclear energy. In fact, as early as 20 y ago, people had realized the importance of risk communication and that a 2-way interactive process among decision makers, experts, and the public should be involved in effective risk communication (94). However, this process has not been well implemented in some countries; for example, China's nuclear policy making relies too heavily on closed expert panels and the public is generally removed from this closed policy-making community (95).

At present, public participation in nuclear power projects has reached unprecedented levels of importance. Worldwide, antinuclear activities have stopped many nuclear reactor projects, even changing some countries' policies on nuclear energy development. Thus, risk communication has become a critical issue. It should be noted that socioeconomic and cultural differences among countries are large, and similar means for communication are not always effective in all countries. For example, when using social media to conduct risk communication, China is more prone to have a rigid language and adopt an evasive attitude toward some issues of public concern, sometimes leading to unexpected results and even strengthening some of the public's dissatisfaction. In contrast, the United States prefers to express the language based on the information category and fully consider the public psychology, achieving relatively good communication effects and overall positive evaluation (96).

Public-Centered Risk Communication. The importance of subjective risk should be fully recognized. Risk communication should be embedded into every phase of risk management, which is an interaction platform among interested parties. The decision making of the nuclear industry should be an open and transparent process to ensure that the public trusts the regulators and nuclear industry. After the Fukushima nuclear accident, public acceptance of nuclear power decreased dramatically in 42 countries, and the not-in-my-backyard syndrome was notable (97). In some countries, the credibility of regulation was even challenged dramatically. To cope with these dilemmas, research institutes independent of regulators, industries, and the public should be established, and they can serve as a bridge to enhance the credibility of regulation and the transparency of information to avoid falling into the Tacitus trap (98). Any safety issue or accident occurring in the nuclear industry should be reported promptly, and the public should be kept informed without any concealing of information. In addition, another premise of risk communication is to continuously strengthen the research on risk perception to help us understand the public judgments of risk and to increase the effectiveness of policies (99). In the unexpected second nuclear era, regulators and nuclear industries should change their moralistic attitudes and establish effective mechanisms for public-centered 2-way communication that can build and maintain sufficient trust in the long term.

Moreover, radiation risk should be communicated correctly, without neglecting its inherent uncertainties. In fact, the public's rejection of NPPs originated from radiation fears. During recent decades, the linear no-threshold (LNT) hypothesis, based on the assumption that, in the low dose range, radiation doses greater than zero will increase the risk of excess cancer and/or heritable disease in a simple proportionate manner, has been considered a proven theory by public opinion, mass media, regulatory bodies, and even many scientists, and this misperception has led to excessive radiation fears. It has been indicated that harms to the public with regard to radiation fears are much more prevalent than those from radiation itself. Finally, it turns out to be an unconservative policy and greatly hinders the process of risk communication (100). For example, there were no prompt fatalities as a result of radiation in the Fukushima accident, but it resulted in public psychological uneasiness in Japan and its neighboring countries and in tremendous economic losses (101). In fact, recent studies on some biological experiments and epidemiological practices have not supported the LNT hypothesis (102–104). Accordingly, low-dose radiation biology should be further studied in the future, and in particular research and development on the LNT hypothesis as well as other competing low-dose radiation models. If it turns out that no-threshold models are incorrect, a practical threshold concept is suggested to be introduced in radiation protection, namely, defining a specific dose level. If the exposure is lower than that level, there will be no observable cancer or genetic effect; establishing this threshold would be helpful in eliminating radiation fears.

Conclusion

Since the beginning of nuclear power there has been no doubt about its value. However, nuclear power is still far from being widely accepted as sustainable energy. In the unexpected second nuclear era, some new realities have emerged with the growth of nuclear energy in developing countries, with more potential risk factors. Nuclear safety is playing an important role in the development of nuclear energy. We have rethought nuclear safety from the sociotechnical perspective and clarified its nature of uncertainty and impact on humans, both physically and mentally. We have also pointed out future trends in nuclear safety philosophy based on a historical review of nuclear safety research. 1) Social rationality-based risk decision making: More attention should be paid to the consequences of psychological trauma, environmental contamination, and so on, rather than to the consequences of physical harm, as was done in the past. To support decision making regarding acceptable risk, the idea of social rationality should be applied to integrate the social and technical elements of the system. 2) Wuli–Shili–Renli-based risk control: The comprehensive effect of 3D factors, Wuli–Shili–Renli, should be considered in risk control. Entity-centered safety theory is being replaced by relationship-centered safety theory. The emphasis on system reliability has changed to an emphasis on the improvement of system resilience. Studies of OiD and resilience engineering should be enhanced to complement the DiD philosophy, while breakthroughs in nuclear reactor physics and design are needed to reduce the impact from uncertainties and achieve "built-in" safety. 3) Technical humility-based risk assessment: systems thinking and social mechanisms should be coupled in risk assessment. Systems thinking should be substituted for reductionism, and advanced technologies such as AI and big data should be integrated to realize more comprehensive and realistic assessment. Besides recognizing the insufficiencies of risk assessment, we should shift from technical optimism to humble practice. More attention and resources should be devoted to designing social mechanisms to address uncertainties. 4) Public-centered risk communication: Attention must be paid not only to objective risk but also subjective risk. Public participation should be strengthened in the decision-making and regulatory processes of nuclear power development. In addition, we should reinforce the independence of nuclear regulation and establish risk communication mechanisms centering on humans, especially for developing countries. Meanwhile, the LNT hypothesis needs to be further studied to alleviate the public's unnecessary fear of radiation and ultimately build and maintain sufficient trust in the long term.

Note that the proposed approaches of improving nuclear safety from a sociotechnical perspective could be useful not only for existing nuclear suppliers but also for newcomers with underdeveloped infrastructure. In particular for newcomers, the top-level design of nuclear safety governance system needs to be established as a first step for the implementation of these approaches, taking into account all mentioned aspects related to how nuclear safety is defined, controlled, assessed, and communicated. Technical and management assistance from nuclear suppliers and the international organizations like IAEA would absolutely facilitate this design process.

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