

Review

Diverse and Flexible Coping Strategy for Nuclear Safety: Opportunities and Challenges

Hong Xu ^{1,*} and Baorui Zhang ²¹ Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-sen University, Zhuhai 519082, China² Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100190, China

* Correspondence: xuhong7@mail.sysu.edu.cn

Abstract: The concept and methodology of traditional Defense in Depth (DID) was challenged in the Fukushima nuclear accident. In order to fix the weakness of the traditional emergency strategies of nuclear power plants (NPPs) and to enhance the DID for nuclear safety, the U.S. Nuclear Energy Institute (NEI) put forward the concept of Diverse and Flexible Coping Strategies (FLEX) for the special purpose of beyond-design-basis external event (BDBEE) hazard mitigation and the corresponding FLEX support guidelines (FSG). The theory has been wildly spread and accepted by many countries that generate nuclear power. The research on the FLEX strategy is a new trend in nuclear engineering in the recent decade. It provides not only fixed on-site equipment/devices but also on- and off-site portable resources to strengthen the reliability of the nuclear safety system, especially for the disaster/hazards (similar to the Fukushima nuclear accident) triggered by BDBEEs. After a brief introduction of the FLEX strategy, four opportunities and ten challenges are summarized. Subsequently, in view of these challenges and technical difficulties, five suggestions for future work are recommended.

Keywords: nuclear safety; diverse and flexible coping strategies (FLEX); defense in depth (DID); beyond-design-basis external events (BDBEE); Fukushima nuclear accident; nuclear accident management; FLEX support guidelines (FSG)



Citation: Xu, H.; Zhang, B. Diverse and Flexible Coping Strategy for Nuclear Safety: Opportunities and Challenges. *Energies* **2022**, *15*, 6275. <https://doi.org/10.3390/en15176275>

Academic Editor: Dan Gabriel Cacuci

Received: 11 August 2022

Accepted: 24 August 2022

Published: 28 August 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Nuclear generation has increased successively these years, which has made a growing contribution to supplying clean and reliable electricity in the world [1]. Nuclear energy has the potential to contribute to a sustainable solution for the world's growing energy needs and environmental problems [2]. Currently, the development of the nuclear industry faces economic, environmental, and safety concerns, but the root of the concerns is nuclear safety [3]. The concept and methodology of Defense in Depth (DID) was brought out at the end of the last century for nuclear safety, and then it spread around the world [4–6]. However, the concept of DID before the Fukushima nuclear accident (called the traditional DID) mostly focused on design-basis accidents and severe accidents, which were mostly triggered by the internal events of the nuclear power plant (NPP) and seldom considered the hazard caused by beyond-design-basis external events (BDBEE). As shown in the Fukushima nuclear accident, BDBEEs may lead to the Extended Loss of Alternating current (AC) Power (ELAP) and the Loss of Ultimate Heat Sink (LUHS), which cannot be mitigated by the strategies of the traditional DID. This weakness of the traditional DID led to the disaster of the Fukushima nuclear accident. In order to fix the weakness, the U.S. Nuclear Energy Institute (NEI) put forward the concept of Diverse and Flexible Coping Strategies (FLEX) for the special purpose of BDBEE hazard mitigation and the corresponding FLEX support guidelines (FSG). They were inspired by the Extensive Damage Mitigation Guideline (EDMG), which was developed by the U.S. NEI owing to the motivation of the 911 terrorist attacks [7,8]. The FLEX strategy has been modified from draft revision 0

in 2012 [9] to version 5 in 2018 [10] owing to its importance and urgency. Subsequently, the idea of the FLEX strategy was accepted all over the world. Xu and Zhang [11] have summarized the FLEX strategies in different countries (e.g., USA, Canada, France, Spain, Korea, and China, etc.) after the Fukushima accident. It should be emphasized that different countries adopted the FLEX strategies but may have different nomenclatures. For example, a similar concept in France is called “hardened safety core”. Additionally, the idea of the FLEX strategy has also been accepted by the International Atomic Energy Agency and the usage of portable/mobile equipment in the FLEX strategies has been adopted and emphasized in several newly issued reports [12–14]. Compared with the traditional installed equipment, the usage of portable/mobile equipment in the FLEX strategies will increase the complication of accident management. The complication comes from two items: (a) the scenarios (the ELAP and LUHS) themselves compared to traditional design basis accidents; (b) the portable equipment, especially the off-site equipment. Additionally, the monitoring measurements of the FLEX strategies (by using the technology of the Internet of Things), which will improve the intelligence level of accident mitigation, may also bring complication to the implementation.

The implementation of the FLEX strategy is a new focus for nuclear safety. Since the U.S. NEI proposed this concept, great progress has been made with the efforts of nuclear scholars and engineers. The theory of the FLEX strategy has been more and more systematic and sophisticated, and its application more and more widely used. However, as a newly developed theory in the recent decade, it is difficult to come to the conclusion that it is already perfect only 10 years after its birth (the constant updating of the U.S. NEI also implies the imperfection of the theory). It is necessary to promote and optimize the concept of the FLEX strategy. More relevant technical details need to be concentrated on. Consequently, the currently existing opportunities and the challenges of the FLEX strategy deserve to be identified and summarized. This is one of the two objectives of this article. The other objective is to recommend several pieces of future work associated with the FLEX strategies.

The rest of the contents of this work are as follows: Section 2 will present the background, namely, a brief introduction of the FLEX strategy; the opportunities and the challenges of the FLEX strategy were summarized and will be introduced in Sections 3 and 4 separately; based on the opportunities and the challenges, some recommendations for future work on the FLEX strategy will be presented in Section 5; and the conclusions of this work will be summarized in Section 6.

2. Brief Introduction of the FLEX Strategy

The contents of the FLEX strategy are summarized and divided into three parts. For more detailed information, the review article by Xu and Zhang [15] can be resorted to.

2.1. Resources

In order to achieve the indefinite coping capability to prevent damage to the fuel in the reactor and the Spent Fuel Pool and to maintain the containment function under both an ELAP and a LUHS following a BDBEE, FLEX provides a phased approach that utilizes installed equipment, on-site portable equipment, and pre-staged off-site resources. Therefore, proposed by the U.S. NEI, the mitigation measures of FLEX could be divided into three phases [9,10], as shown in Table 1 (an overlap during the phase transformation may exist to leave enough margin and time for the introduction of the equipment in the next phases [16]). The examples of resources in the table are summarized based on a variety of literature. The most significant difference between the FLEX strategy and Emergency Operating Procedures (EOPs) or Severe Accident Management Guidelines (SAMGs) is that the former uses portable equipment/devices but the latter does not. In the old framework of nuclear safety, the portable (normally off-site) equipment and devices are only used for the level of post-severe accidents [17]. It should be emphasized that the maintenance and

testing of the resources are very crucial for the success of the FLEX strategies. Portable equipment should be subject to maintenance and testing to verify proper function [18].

Table 1. Phases for FLEX strategy implementation.

Phase	Staging Time	Types of Resources	Resources (Examples)
1	0–8 h	Installed equipment and devices	• Station batteries • Turbine driven auxiliary feed water (TDAFW) • Steam generator (SG) pilot operated (safety) relief valve or atmospheric depressurization valve (PORV/ADV)
2	8–72 h	On-site portable equipment/consumables	• mobile diesel generator • portable batteries and chargers • portable lightning • portable pumps • hoses and couplings • air compressors • equipment for clearing debris • equipment for temporary protection against flooding
3	72 h	Off-site resources	• fresh water (from the firefighting system and the ultimate heat sink, e.g., water from a lake or river nearby) • diesel fuel • electrical generators • large mobile pump • high-capacity spray pump

2.2. Development of the FLEX Strategy

Based on the FLEX strategy development procedure for flood hazards proposed by the U.S. NEI [10], a more generalized detailed procedure of the development and assessment of the FLEX strategies is shown in Figure 1.

Both the probabilistic safety assessment (PSA) method and deterministic simulations using system thermal-hydraulic (STH) codes are used for the development of the FLEX strategy [19–21].

Since each plant and site has unique features, the implementation of FLEX capabilities must be site-specific. During the establishment of the FLEX strategy, the U.S. NEI has provided a guideline for the development of the FLEX strategy, which includes three steps [10]:

- (1). establish a plant-specific baseline coping capability.
- (2). determine applicable site-specific BDBEEs.
- (3). identify enhancements to the baseline capability to address applicable site-specific scenarios.

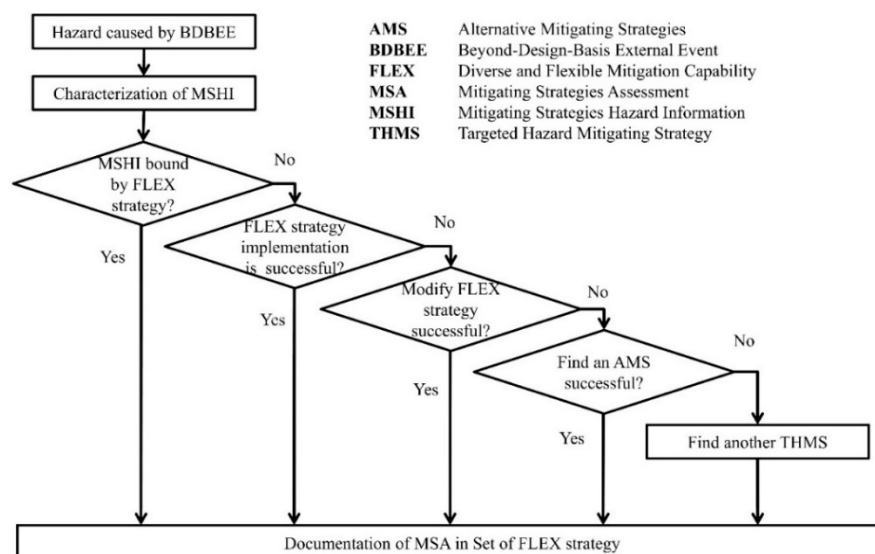


Figure 1. Procedure of Mitigating Strategies Development and Assessment.

2.3. Staffing and Training

A crucial lesson learned from the Fukushima event is that there are increased staffing demands following a BDBEE. Normally, it is assumed that all the personnel on-site are available to support the site's response to a hazard owing to a BDBEE and that the on-site staff do not consider independent, concurrent events, e.g., no active security threats. Additionally, the on-site staff are at site-administrative minimum-shift staffing levels, including additional staffing that is procedurally brought on-site in advance of a predicted BDBEE [22]. The key elements for staffing and training include staffing assessments, training and drills, a human reliability analysis, and a communication mechanism.

3. Opportunities

Before starting this section, it is necessary to explain the idea of opportunity in this article. The “opportunity” in this article is defined as “a (positive) benefit that may be achieved by developing and implementing the FLEX strategies.” It may be a developing research field that had no special attention to the study of FLEX equipment/devices before and consequently has the chance to develop further when considering the usage of portable equipment/devices, to make up some technical defects or offer some kind of advantage for nuclear safety.

The developed FLEX strategy led to several opportunities from different viewpoints. According to the knowledge/experience of the authors in deterministic safety analysis [23–25], PSA, severe accident mitigation [26], nuclear accident mitigation strategies [27,28], machine learning method application in nuclear engineering [29], and their review work on the FLEX/EDMG strategy [8,11,15], the dominant four opportunities related to the FLEX strategy are summarized as follows.

3.1. Concept Enhancement of DID and Theory Improvement for Nuclear Safety

The motivation for developing the FLEX strategy is to enhance the concept of DID and to improve nuclear safety itself, based on a more flexible strategy using portable equipment/devices, compared with the traditional EOPs/SAMGs accident management framework that uses the fixed safety systems. With the development and more detailed understanding of DID, a hidden weakness of the traditional DID (before the Fukushima nuclear accident)—the cliff-edge effect (CEE), which is caused by BDBEEs [30,31]—has been focused on in the recent decade. Based on the identified accident sequences following the BDBEEs and cliff edges at each NPP, the objective of the FLEX strategy is to improve

the resilience and flexibility for the prevention and mitigation strategies of the NPP, and consequently enhancing the DID [9,32].

Additionally, the FLEX guidelines require an “N + 1 criterion”, which means that no matter how many units are on-site, there must be that “many plus one” pieces of equipment, connection points, and so on, to provide DID [33].

3.2. Promotion of Discipline Development

As an important part of nuclear engineering, nuclear safety involves tremendous work in various disciplines throughout the whole life of the NPP from the design, construction, and operation to decommissioning, especially during the period of accidents.

The development and implementation of the FLEX strategy refer to multiple disciplines including safety analysis, equipment reliability and maintainability, human factors engineering, radiation protection, strategic management and economics [34,35], etc., as shown in Table 2. The studies of the FLEX strategy should be considered in a manner of these multi-disciplinary aspects, and on the other hand, these disciplines will also benefit from the FLEX strategy studies. It should be noted that the disciplines in Table 2 are not all inclusive and, furthermore, the importance of management science should be focused on or highlighted in addition to the natural and engineering sciences. The disciplines are not independent but interdisciplinarity may be more prevalent from the viewpoint of comprehensive or systemic studies, since it is obvious that a multi-discipline integrated system of the FLEX strategies is more powerful for assistance during a BDBEE.

Table 2. FLEX strategy involved disciplines and examples.

Discipline	Examples of Applications in FLEX Strategies
Nuclear safety	- the thermal-hydraulic analysis of accident transient during the implementation of FLEX strategies - the simulation of release/source and distribution of radiation
Equipment reliability and management	- the analysis of the reliability of the involved portable equipment/devices - the management of portable equipment/devices (the storage, implementation, maintenance, protection, and policies)
Probabilistic safety assessment (PSA)	- the identification of initial BDBEEs that lead to severe hazards - BDBEE accident consequence evaluation
Human factors engineering (HFE)	the reliability of plant personnel during the implementation of FLEX strategies
Radiation protection	radiation protection of plant personnel during the implementation of FLEX strategies
Strategy optimization and economics	- the optimization of the candidate of FLEX strategies - economic analysis for the management of portable resources

Table 2. Cont.

Discipline	Examples of Applications in FLEX Strategies
Logistics and transportation	• emergency logistics management • logistics and transportation optimization for off-site resources during a BDBEE including the induced barriers
Software engineering	• the development of analysis codes for the BDBEE scenario • the development of a simulator for personnel training
Internet of Things, big data, and machine learning	• the arrangement of sensors, measured data collection, and the analysis of key data during a BDBEE • path optimization for the implementation of FLEX strategies • the fragility assessment of structures, systems, and components (SSCs), i.e., the reactor, the SFP, the core and SFP cooling systems, the containment, and the conditions in the areas where local actions must be executed • the digital twin [36] of SSCs to assist the implementation of FLEX strategies
Artificial intelligence and robotics	• remote control for FLEX strategies • the implementation of FLEX strategies using robotics (including measurements) • virtual reality (VR), augmented reality, and mixed reality (MR) technologies for BDBEE scenarios and FLEX strategies
Emergency management	• staffing management for the implementation of FLEX strategies • management of on-site and off-site FLEX resources • mass evacuation plan and the organization during a BDBEE
Social studies	• public psychology during a BDBEE • public reaction during a BDBEE • the satisfaction of basic human needs (food, water, shelter, sanitation, and medical) during a BDBEE

3.3. Promotion of On-Site and Off-Site Joint Response Mechanism

The NPP is not isolated from the environment. In the case of an accident, it should maintain good communication and coordination with the outside world. The nuclear accident triggered by a BDBEE needs off-site support measures to mitigate the hazards and it may also lead to significant off-site consequences in the surrounding area and population. These consequences can be mitigated by developing emergency measures and response plans that can be exercised regularly and implemented during an accident [37].

The FLEX strategy is one of the measures that may mitigate the potential widespread contamination outside of NPPs during a BDBEE. However, to implement the FLEX strategies effectively, the establishment of on-site and off-site joint response mechanisms is very crucial. At the beginning of the accident, the domestic atomic energy authority and gov-

ernmental authorities should be notified immediately. In the traditional framework for accident mitigation, an emergency organization group that consists of NPP licensees, an emergency director, reactor supervisors and operators, health physicists, and other technical experts in nuclear engineering and system engineering, etc., should be built promptly. The group will evaluate the accident impacts qualitatively or quantitatively from the view of multiple disciplines [38] and will develop an integrated response to the BDBEE based on their conclusions, including the important actions to be taken to stop the progression of an accident or to safely shut down the facility [39]. The resources will be managed by the group.

The introduction of the FLEX strategy may lead to the reconsideration of the on-site and off-site joint response mechanism, especially how to maximize the effectiveness of the involved portable resources of the FLEX strategy. Additionally, regional response centers (also called FLEX support centers) were specifically built in some countries for the implementation of the FLEX strategy after the Fukushima nuclear accident [40,41].

3.4. Improvement of the Nuclear Safety Culture

There is quite a huge deviation in the concrete concept of safety culture since the definitions of scholars' safety culture are not raised. No matter from the viewpoint of the vertical (historical) or the horizontal (in different fields) comparison, the safety culture has changed a lot [42]. The nuclear safety culture was raised by the International Atomic Energy Agency after the Chernobyl accident in 1986, which became the starting point of official discussion on safety culture. Nuclear safety culture was the most preferential safety principle and it emphasized the importance of organization and workers' overall attitudes on safety [43]. The safety culture scope was gradually expanded, including the hardware aspect (such as safety facilities), software aspect (such as operation procedures or quality activities), and organizational factors (including workers' attitude).

The main factors that could significantly influence the safety culture are the following: the regulatory environment, organizational environment, worker characteristics, socio-political environment, national culture, organizational history, business environment, and work/technology characteristics [44]. Each well-known nuclear accident (for example, the Three Mile Island Unit 2 nuclear accident, Chernobyl nuclear accident, and Fukushima nuclear accident) has strengthened the contents of nuclear safety culture [45]. Consequently, the requirements to improve the safety culture after the Fukushima nuclear accident were essential [46]. The FLEX strategy, which is the most crucial modification after the accident, has a significant impact on nuclear safety culture, as shown in Figure 2. It shows that in the case of the implementation of the FLEX strategy being applied, the nuclear safety culture will be enhanced correspondingly.

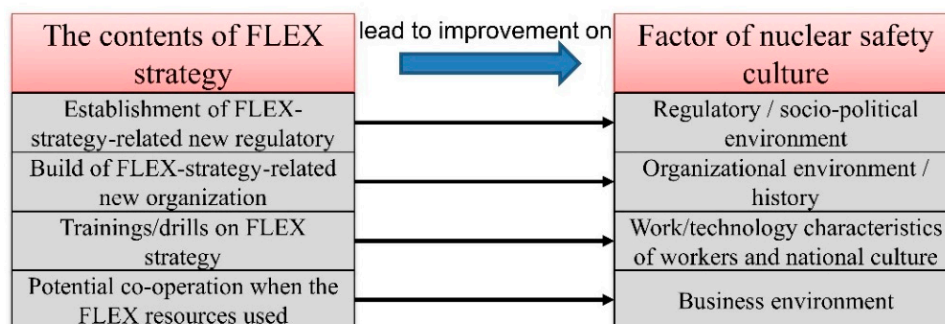


Figure 2. The impact of FLEX strategy on nuclear safety culture.

4. Challenges

Despite several opportunities of the FLEX strategy that are shown and discussed above, it also faces its own unique set of technical/managerial challenges to development and application. The challenges of the FLEX strategy are analyzed in this section. The

“challenge” here refers to “a key technical point or difficulty that has been encountered and needs to be resolved during the development and implementation of the FLEX strategies”. For example, it may be a concept that needs further discussion, is a methodology to be developed, or is a new technology that has the potential to be applied in the FLEX strategies.

There is no denying that inside every opportunity are hidden challenges, which have been identified by us and are shown in Table 3. It should be emphasized that the corresponding relationship between the opportunities and challenges is only a rough classification and is not rigorous since there is no clear definition for each opportunity/challenge and their connotations may be overlapping. All of these challenges must be addressed through research and development in the future. It should be realized that we do not identify the challenges for the “improvement of the nuclear safety culture” since the nuclear safety culture is more than a technical concept but also a regulatory and political one in different countries.

Table 3. Challenges for each opportunity during development and application of FLEX strategy.

Opportunity	Challenge
concept enhancement of DID and theory improvement for nuclear safety	knowledge of CEEs
	credit FLEX strategy in the PSA/determination method
	FLEX strategy time constraint
	emergency management
promotion of discipline development	measurement and data analysis
	strategic economic considerations
	uncertainty and sensitivity analysis
	human/equipment reliability
promotion of on-site and off-site joint response mechanism	equipment management and staging routing
	strategy for the multi-unit site
improvement of the nuclear safety culture	-

Each challenge is interpreted briefly as follows.

- (1) knowledge of CEEs: BDBEEs may challenge the safety functions of NPPs and lead to severe accidents. Enhancing the understanding of the challenges that NPPs face under BDBEEs and possible new phenomena based on CEEs that may be introduced is crucial for the development of the FLEX strategy [47,48]. Especially, the common causes of failure, which are the kind of CEEs and the challenge of understanding the nature, need to be paid attention to in the BDBEEs analysis [49,50].
- (2) credit FLEX strategy in the PSA/determination method: both the PSA and determination method are used for technical evaluations and formal calculations to validate the capabilities and effectiveness of the FLEX strategy [51]. The verification and validation (V & V) of the strategy should be highlighted in the future. Furthermore, the trend is to combine the PSA and determination methods together to build a comprehensive methodology [52], which rarely appears in the literature.
- (3) FLEX strategy time constraint: the characteristics and phenomena change quickly during the accident transient. In the case that the time limit/window of the FLEX equipment deployment is not satisfied, the strategy cannot be effective. Specific methodologies (for example, the sensitivity study [53]) need to be introduced to ensure the time constraint can be met. It is suggested that the time window for the installation and deployment of the FLEX equipment should be considered quantitatively by the method of spatiotemporal analysis [54].
- (4) emergency management: at present, there is a large scatter in EOPs, SAMGs, EDMG, and FLEX, etc. As the goals of plants' accident management tools are almost identical,

it is amazing that so many different approaches exist. In order to strengthen the emergency management level for nuclear safety under BDBEEs, the integration of the EOPs/SAMGs with FSGs/EDMGs is essential work for the future [55,56]. Furthermore, most of the literature about the FLEX strategy focused on Light Water Reactors. It is strongly suggested for other kinds of NPPs (including the new types of NPPs under development) since their emergency management is much different.

- (5) measurement and data analysis: the measurement in the accident is very important for the analysis of the scenario and the implementation of the strategy [57]. However, the lack of measurement data or the failure of the measurement may lead to a handicap for data analysis. The Internet of Things used in the NPPs, which is the basic technology for the corresponding digital twin of the NPP and the remote response (e.g., the remote emergency response robot), may be challenged by the extreme scenario. Specific methods, such as the artificial neural network [58], should be introduced or developed for this issue to support the analysis of the FLEX strategy.
- (6) strategic economic considerations: some researchers began to consider the economical characteristic for the use of portable equipment/devices [59,60]. However, a more detailed methodology needs to be established for quantitative analysis.
- (7) uncertainty and sensitivity analysis: the portable equipment in the FLEX strategy is more “flexible” than the traditional installed equipment, but more “flexible” also means more “uncertainty” during its usage. Uncertainty and sensitivity analyses are suggested for the FLEX strategy implementation [61]. A new uncertainty methodology may be introduced or developed for the deployment of FLEX equipment/devices. The uncertainty related to the FLEX strategy is from several kinds of sources, for example, the scale of the BDBEE and its affected area [62], the unknown or ambiguous phenomena that may occur, the models in the STH codes (which are used for accident analysis), etc.
- (8) human/equipment reliability: compared to the traditional installed equipment (they are normally automatically controlled by the operators in the control room), the usage of “flexible” equipment may introduce the local manual operation which will lead to a higher risk of human errors. In order to achieve the objectives of the FLEX strategy, the reliability of both operators of the equipment should be considered in detail, using specific methodologies such as the human reliability analysis (HRA) method [63] and Bayesian theory [64].
- (9) equipment management and staging routing: in principle, FLEX equipment is available in redundancy and is stored separately. Some countries (such as the USA and Canada [65]) have built specific Emergency Mitigating Equipment Guidelines that can be used for the management of the FLEX equipment. However, BDBEEs may induce challenges to the protection of FLEX equipment, the deployment of FLEX equipment, and considerations in utilizing off-site resources [66]. Additionally, the on-site staging routing is strongly based on the situation of the affected site, especially the accessibility and radiation level of the target area for equipment deployment.
- (10) strategy for the multi-unit site: more attention should be paid to the FLEX strategies for multi-unit sites since the BDBEE may lead to more severe hazard to them and the FLEX strategies will be more complicated [67], especially in countries with a high density of units on one site (for example, South Korea) [68].

5. Future Work Recommendation

To address some of the above-mentioned challenges, the following pieces of future work are recommended. It should be noted that each part of this section deserves a separate discussion in the case of a detailed study. Here, only some brief recommendations are given, without going into detail. Additionally, since most of the recommended work involves the development of systems, which may only have the basic functions (dealing with fewer challenges) or powerful capabilities (dealing with more challenges) depending on the different stages of development, it is hard to identify the relationships clearly. It is assumed

that the recommended work is just at the beginning. We try to clarify these relationships in the context of this section.

5.1. More Detailed PSA Analysis of the FLEX Strategy

Implementing EOPs/SAMGs/EDMGs/FSGs based on a PSA is very important since the analysis result will indicate whether risk is indeed reduced by applying the various accident management strategies. Generally speaking, the inclusion of procedures/guidelines into the PSA may be a complex matter, for which the industry standards at present do not give proper guidance [69,70]. The U.S. NEI provides a guide to performing the PSA analysis for FLEX strategy, which is categorized into three tiers [71]: Tier 1 follows a qualitative approach; Tier 2 uses a semi-quantitative approach with a decision tree; and Tier 3 utilizes a full PSA model to quantify the effect of the FLEX strategy to the NPP risk. Several pieces of research have introduced integrated safety assessment, using a dynamic PSA, to NPP accident and FLEX strategy analysis [72,73]. Although these studies have made some progress, if the PSA method is to be used more deeply in FLEX strategy research, the following problems should be addressed in the near future, because their results directly affect the development and implementation of the FLEX strategies.

(1) Multi-unit and multi-site PSAs

FLEX strategies are needed to address not only the risk from a single unit of an impacted site but also the overall risk from all reactor units located at the same NPP site. Furthermore, natural events may affect more than one unit (as happened in the Fukushima nuclear accident). As the 10th item (the strategy for the multi-unit site) of the identified challenges above, in the case of wide-area damage and simultaneous accidents on several units, the response organizations would be confronted with multiple challenges requiring actions and resources at several units at the same time [56]. This results in the limited effectiveness of the FLEX equipment, which finally leads to the FSGs for the multi-unit site [74] or multi-site scenario for the deployment of the equipment. Accident management under a BDBEE scenario at a multi-unit site or multi-site scenario requires cross-cutting and inter-disciplinary coordination and cooperation among in-house organizations and inter-organizations [75], which makes the on- and off-site situations much more complex and correspondingly difficult to introduce FLEX strategies. Some codes [76,77] already have the capability of dealing with simple multi-unit PSA models, but more detailed methodologies need to be developed for the FLEX strategies.

(2) Human reliability analysis (HRA)

There appears to be not much research with respect to the human aspects of decision making in an NPP accident, especially the FLEX strategies, which are more flexible and more dependent on humans compared to traditional procedures, although more attention has been paid to it in recent two years. The human error probability (HEP) estimated for the human failure events by the HRA Calculator of the Electric Power Research Institute (EPRI) showed that it was a key factor and could not be ignored during the PSA analysis [71]. According to the literature [48,71], some of the actions related to the deployment of FLEX equipment that may not be explicitly addressed in existing guidance or provided in HRA tools include:

- (1) decisions to enter a procedure and the time window evaluation (i.e., the third item of the identified challenges);
- (2) command and control evaluation for the FLEX strategy;
- (3) actions to transport and install portable equipment;
- (4) complex actions needed to achieve strategies, for example, actions that require many people working in coordination to complete a single task.

Therefore, to deal with the eighth item (human/equipment reliability) of the challenges above, human engineering aspects for the FLEX strategy should be considered in detail [78]. Human failures during the implementation of FLEX strategies can be evaluated using several methods, such as the Cause-Based Decision Trees Method, Standardized Plant

Analysis Risk-Human (SPAR-H), and Technique for Human Error Rate Prediction methodologies [79,80]. Estimation of HEPs in association with deploying portable equipment has been identified as an important issue for HRA application in the FLEX strategy [81,82]. Kim and Cho [83] have identified several challenges for the HRA application. Xu and Zhang [15] have reviewed several scholars' work and developed methods on the HRA for the FLEX strategies. Recently, some progress on the dedicated HRA methods for the FLEX strategies implementation was made by the U.S. Nuclear Regulatory Commission (NRC) and the Korea Atomic Energy Research Institute (KAERI) independently. The U.S. NRC has developed two methods (i.e., expert elicitation [84] and the Integrated Human Event Analysis System for Event and Condition Assessment (IDHEAS-ECA) [85]) to obtain HEPs and to understand the performance-influencing factors involving the use of portable equipment. Suh et al. [86] have developed a time-based model to classify two time-distribution functions (i.e., the time required and the time available) to calculate HEPs from delayed action when implementing strategies associated with the use of portable equipment. However, the following issues should be highlighted for the introduction of these HRA methods into the FLEX strategy analysis.

Owing to the limited and rare dataset of the human performance and errors on human actions for the FLEX strategies, the U.S. NRC proposed the expert elicitation methodology to estimate HEPs for a representative set of FLEX actions and to identify the factors impacting the HEPs. Obviously, to execute an HRA for the FLEX strategies, building relevant extensive datasets is very crucial work. Considering that the FLEX strategies vary from plant to plant, plant-specific information is also included in the datasets. Systematic approach training programs that include the FLEX strategies are useful for their implementation and dataset creation.

Since the time required to implement the FLEX strategies has a high level of uncertainty and the HEPs are very sensitive to changes in scenario context or action specifications, sensitivity and uncertainty studies are inevitable for HEP estimation [86,87]. Furthermore, optimized methodologies (for the procedure and time window optimization) may be adopted to increase the likelihood of success of the FLEX strategies and to decrease the HEPs [88].

Some detailed errors for human reliability should be considered in HRAs before their application in a FLEX strategy analysis. For example, SPAR-H, developed by the U.S. NRC, did not consider communication errors, which are very important for the implementation of FLEX equipment [89].

(3) Cost-benefit analysis of the FLEX equipment

Decision making is an important part of NPP operation and accident prevention/mitigation. It involves decisions that may have significant safety and economic consequences. A cost-benefit analysis is based on the ratio between the risk importance measures and the cost of the safety measure. Cost is a parameter of the safety measure. To handle the sixth item (strategic economic considerations) of the challenges above and to achieve a balance between the safety and economic consequences, a cost-benefit analysis would support safety measures that have a minimal cost in one-by-one comparisons [90].

It is generally considered that the safety considerations far outweigh the economic considerations during BDBEES. In other words, making the decision-making process more efficient can result in potentially large economic benefits [91]. Therefore, the cost of FLEX equipment is not a crucial point in BDBEE scenarios. However, the benefit of utilizing the FLEX equipment during normal operations to the NPP is an interesting issue [59,60].

5.2. BDBEE Analysis and Supporting System

Since the nuclear accident, especially since the scenario triggered by a BDBEE is very complicated, a comprehensive BDBEE analysis and supporting system is very useful for nuclear accident management. In this section, a system that specifically deals with the FLEX strategy is proposed. The process of the BDBEE analysis and supporting system is as follows.

(1) BDBEE characterization analysis

BDBEEs have been grouped into five types by the U.S. NEI: (a) seismic events; (b) external flooding; (c) storms such as hurricanes, high winds, and tornadoes; (d) heavy snow, ice storms, and extreme cold; (e) and finally extreme heat [92]. This step of the process focuses on the identification and characterization of the applicable BDBEEs for each site. Identification involves determining whether the type of hazard applies to the site and finding its CEE hazard (the first item of the identified challenges, i.e., knowledge of CEEs). Characterization focuses on the likely nature of the challenge in terms of timing, severity, and persistence. In the case of too many parameters or characteristics being involved, the dimension of the data can be reduced by methods such as the principal component analysis [93].

(2) Fragility assessment of NPP critical SSCs

Fragility assessment (for example, for seismic margins) for a BDBEE is crucial but was seldom performed in the past. The plant-specific thresholds for critical SSCs are determined based on the fragility assessment. Fragility analysis is based on several methods, such as Artificial Neural Networks [94] and (dynamic) Bayesian networks [95]. The output of this step is a table of SSCs that are assessed in the NPP response model, as well as their failure probabilities as a function of the severity of the BDBEEs (e.g., fragility tables, fragility curves, or failure models based upon BDBEE characteristics based on the last step) [96].

(3) Strategies development and V & V

The V & V of procedures must be performed to ensure that guidance can be followed and time limits can be met. For the development and V & V of the FLEX strategy, the trend is to combine the PSA method and deterministic simulation using STH [97,98], as shown in Figure 3, which starts with BDBEEs identification. This process is corresponding to treating the second item of the identified challenges, i.e., the credit FLEX strategy in the PSA/determination method. After the preliminary selections for all kinds of BDBEEs which may exist at the specific NPP site have been made, the PSA analysis is used for the selection of risk-informed scenarios [99]. After the scenarios are confirmed, the corresponding initial conditions and boundary conditions are determined. Then, the STH codes may be introduced for the scenario modeling and simulation. According to the simulation results and the experience database (for example, the seismic and operational database [100]) or a built expert system [101], or the results of the PSA analysis directly, the targeted measures, which are aimed to minimize the risks of scenarios, could be proposed. The selection of measures and the determination of the corresponding parameters, equipment, and procedures could be an iterative process until the prevention or mitigation of the hazards caused by the BDBEEs is satisfied.

It is appropriate to note here that some important issues should be considered and may be addressed during the development of strategies development and V & V:

- (1) uncertainty analysis (i.e., the seventh item of challenges) is suggested for the evaluation of the stability and convergence of the BDBEE analysis and supporting system;
- (2) the stability and the reliability of the FLEX devices/equipment is an inevitable issue for their implementation;
- (3) special attention should be paid to common causes of failure, especially specific failure-to-start, failure-to-run modes [102];
- (4) it is necessary to validate the FLEX strategies and the related equipment for BDBEEs in the experiment of thermal-hydraulic test facilities if feasible [103].

These issues need to be properly considered/addressed by different methods, for example, the redundancy and of alternative installed equipment/devices.

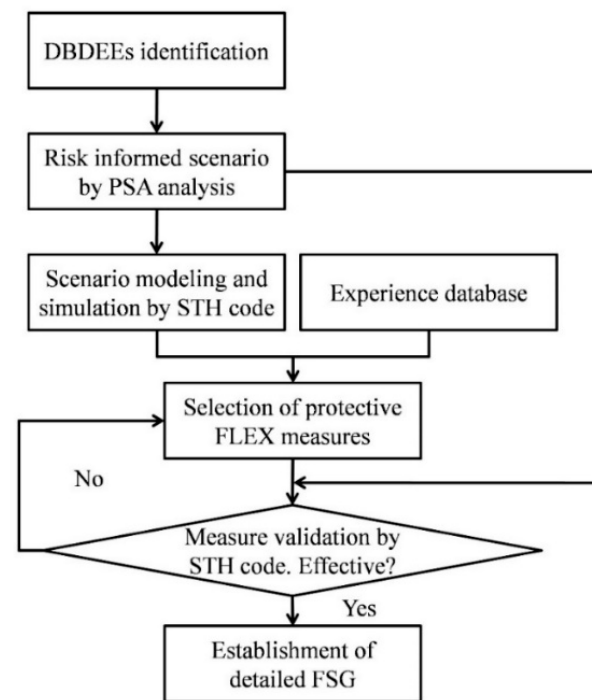


Figure 3. Development of the FLEX strategy.

(4) Build integrated accident management guideline

Since the procedures/guidelines for nuclear safety was developed under different backgrounds, the harmonization and integration of them are different. However, it seems very useful since the procedures/guidelines have similar or related nuclear safety objectives. This step involves the fourth item (emergency management) of the identified challenges. Kim et al. [104] have preliminarily proposed an integrated framework of NPP accident management guidelines, which may be a reference for the strategy development and needs further delicate study.

5.3. Remote Response Technology Enhancement during NPP BDBEEs

An overarching lesson from the Fukushima nuclear accident and other engineering accidents is that major damage to infrastructure in the area surrounding the plant might challenge an effective emergency response [68]. Remote response technology has advanced to the extent that a robot system, if properly designed and deployed, may greatly help respond to NPP BDBEEs [105]. Actually, the emergency robots were used in the Fukushima accident, but they did not play an important role due to technical limitations [106,107]. However, since the Fukushima nuclear accident, there has been increasing interest in developing disaster robots that can be deployed instead of a human operator to the field to perform mitigating actions in the complex and harsh environment of the NPP site. The advantages of the emergency robots, compared with workers, are summarized as follows: shorter procedures to save time, easier procedure control owing to digital operation, higher precision, higher reliability, lower operating environment requirements (especially for radiation), etc.

The objective of this suggested study is to develop and enhance the remote response technology during NPP BDBEEs, including the emergency response robot and its remote control proto-type platform development, consequently to achieve the implementation of the FLEX strategies automatically. To achieve the objective, the fifth item (measurement and data analysis) of the challenges may be encountered and the associated issues in the Internet of Things, Big data, and Digital Twin need to be resolved. Some characteristic concerns for emergency response robot development are illustrated in Figure 4. It should

be emphasized that the “specific functions” in Figure 4 stand for the target functions of the FLEX strategies during BDBEEs.

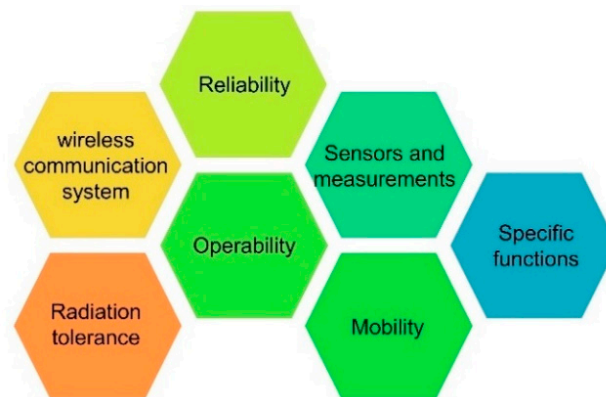


Figure 4. Characteristic concerns for emergency response robot development.

5.4. Emergency Management Support System

An effective response is dependent on integrated planning and response actions among the NPP, national nuclear safety organization, governmental authorities, and industry and vendor support personnel. The emergency management support system is crucial since the NPP emergency management is very complicated, involving multi-lateral coordination [108], especially during the accidents caused by BDBEEs (the site damage and disorder in the surroundings may limit the outside support [69] and the introduction of the off-site FLEX equipment/devices increases the difficulty of accident management), the structure of which could be seen in Figure 5—one commander center and four specific modules to achieve a different target separately. In the commander center, besides the decision group, the information and data interaction (with relevant entities, headquarters, governments, regulations, emergency facilities, and so on) should be included and summarized in the system. To develop such a support system, several challenges in Section 4, especially the ninth item (equipment management and staging routing), may be encountered and resolved. Several principles should be set as the basis for efficient emergency management support operations:

- (1). confirm that the distribution of abilities, skills, and on- and off-site communication are intact;
- (2). possess adaptability as the group develops and changes, either adding or canceling skills as needed [109];
- (3). consider the method of remote control and the strategies to regain control over the site and limit site damage (e.g., firefighting) during BDBEEs;
- (4). confirm the sufficiency of the necessary portable/mobile resources (e.g., AC power, direct current power, water, pneumatic air, diesel fuel) for the FLEX strategy and necessary staff;
- (5). confirm the capability of logistics, especially under the following two conditions: (a) the ultimate “common cause event”—Black Sky Events—with the potential to prevent the off-site world from rendering meaningful assistance to the damaged NPP in a timely manner, and (b) when several NPPs are simultaneously in need of FLEX equipment and resources from the FLEX regional response centers [110];
- (6). confirm the capabilities of simulation, analysis, and consequence evaluation;
- (7). confirm enough measurement to check the condition of the key SSCs;
- (8). evacuate the personnel on- and off-site and take care of wounded people, providing basic medical and sanitation, sanctuary, and daily necessities;
- (9). confirm the capability of improvisation, especially using the on- and off-site FLEX resources, in case of a situation without corresponding procedures/guidelines [111].

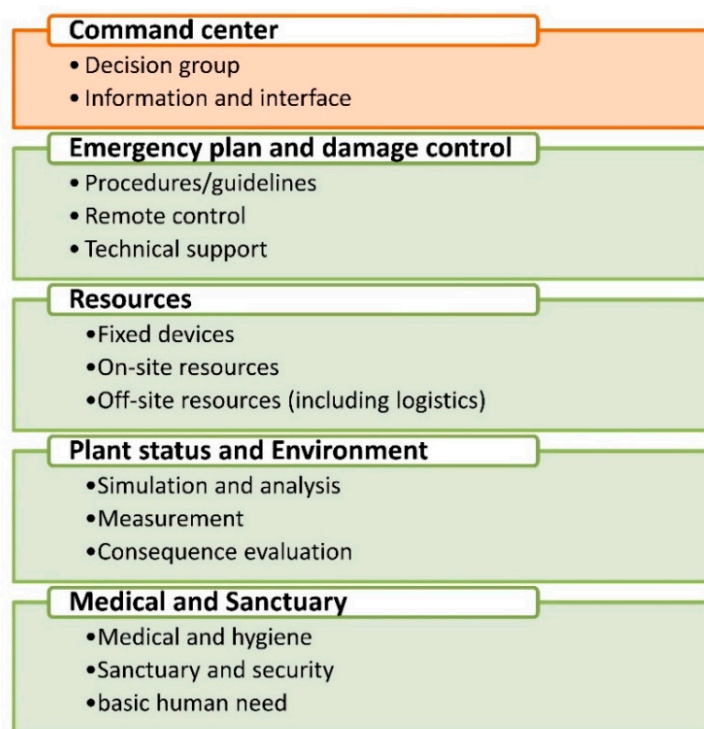


Figure 5. Modules of Emergency management support system.

5.5. Full-Range Simulator for the Multi-Unit Site

During the deployment of FLEX strategies for NPP accident mitigation, human errors, mistakes, learning, decision making, and actions are part of the synergistic learning processes, which are dynamic and time-dependent, as shown and validated against massive integral system accidents and events, and human learning data [112]. Therefore, a truly dynamic restoration theory is required, not a static risk assessment [113]. In order to achieve this objective, a full-range simulator concentrated on the FLEX strategy, especially for the multi-unit sites, is suggested for the near future work. The full-range simulator enabling NPP accident simulations based on the STH best-estimate codes or other accident analysis codes can be valuable in providing a single unifying platform for strengthening and integrating emergency response capabilities, such as EOPs, SAMGs, EDMGs, and FSGs [114,115]. The development of this kind of simulator involves several challenges (e.g., the third item about the FLEX strategy time constraint, the fourth item about emergency management, the seventh item about uncertainty and sensitivity analysis, and the tenth item about the strategy for the multi-unit site, etc.). A typical flow chart of the simulator for a multi-unit site is summarized and illustrated in Figure 6. The different locations of the key SSCs and off-site scenarios are simulated parallelly and an interface is provided for two functions: (a) data exchange for decision making and consequently for the entering of the procedures/guidelines of accident management; (b) human–computer interactions for the training and drills of operators.

Therefore, the simulator can be used to validate or improve the effectiveness of the procedures/guidelines for the FLEX strategy and to provide a realistic and interactive platform to support the training and drills for the related operators. Based on the simulator, the operators can renew their knowledge, improve their behaviors, and finally be qualified in the implementation of FLEX strategies during BDBEEs.

Additionally, experience from major accidents outside of the nuclear field shows that organizations can become destroyed, degraded, and challenged, so “preparing to be unprepared” may be a useful dimension to add for drill/exercise realism [56]. Hence, the full-range simulator may also include improvisation training for the conditions that have never occurred and have never been analyzed before.

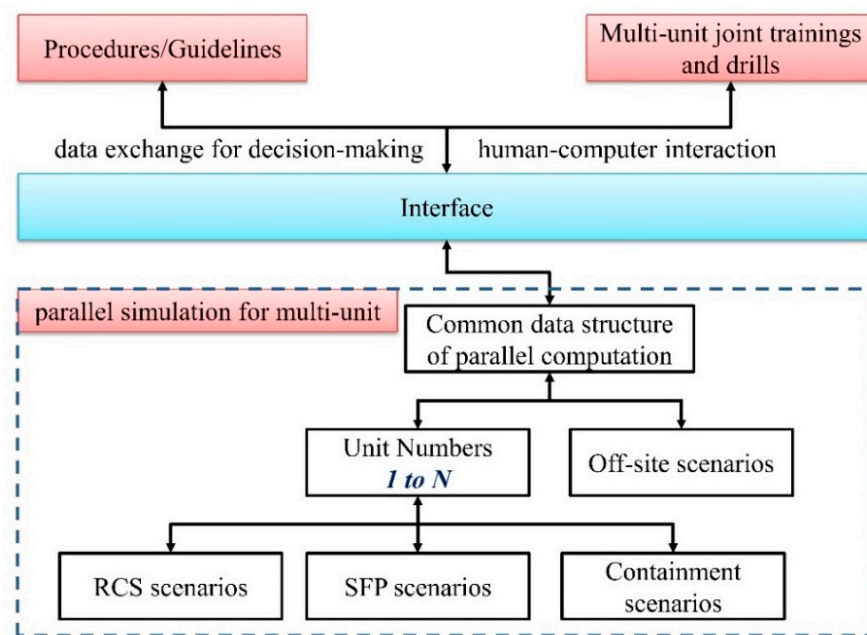


Figure 6. Flow chart of full-range simulator for the multi-unit site (RCS: Reactor Cooling System; SFP: Spent Fuel Pool).

6. Conclusions

After the Fukushima nuclear accident, the concept of the FLEX strategy was put forward by the U.S. NEI. Its theory has been wildly spread and accepted by many countries that generate nuclear power. The research of the FLEX strategy is a new trend in nuclear engineering in the recent decade. It provides not only fixed on-site equipment/devices but also on- and off-site portable resources for nuclear accident prevention/mitigation, especially for the disaster/hazards (similar to the Fukushima nuclear accident) triggered by BDBEEs. However, the research progress of the FLEX strategy has been affected by several unfavorable factors, including the knowledge of CEEs, the V & V methodology of the FLEX strategies, the portable equipment management and staging routing, the FLEX strategy for the multi-unit site, and so on. In view of these challenges and technical difficulties, several suggestions for future work are proposed, such as several topics for a more detailed PSA analysis of the FLEX strategy, a BDBEE analysis and supporting system, and remote response technology, etc. Finally, it should be noted that some topics that were not been emphasized in this paper and this does not mean that they are not crucial for the FLEX strategy. It is only because of the impossibility to list all of the FLEX-strategy-related topics, and the limited time and knowledge of the authors. For example, experimental studies of the FLEX strategies are also important from the viewpoint of some researchers, and there were rarely experimental studies on the FLEX strategies, especially for those that introduced new equipment or devices for strategy implementation. Consequently, it should be focused to some extent in the future.

Author Contributions: Both of the authors made valuable contributions to this review work. H.X. and B.Z. both connected the literature, summarized the key points of each literature and reviewed on them. The manuscript was written by H.X. with the help of B.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AC	Alternating Current
CEE	Cliff-Edge Effect
EDMG	Extensive Damage Mitigation Guideline
EOP	Emergency Operating Procedure
FSG	FLEX Support Guideline
HRA	Human Reliability Analysis
LUHS	Loss of Ultimate Heat Sink
NPP	Nuclear Power Plant
PSA	Probabilistic Safety Assessment
SAMG	Severe Accident Management Guideline
SPAR-H	Standardized Plant Analysis Risk-Human
STH	System Thermal-Hydraulic (code)
BDBEE	Beyond-Design-Basis External Event
DID	Defense in Depth
ELAP	Extended Loss of Alternating current (AC) Power
FLEX	Diverse and Flexible Coping Strategy
HEP	Human Error Probability
KAERI	Korea Atomic Energy Research Institute
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission
RCS	Reactor Cooling System
SFP	Spent Fuel Pool
SSC	Structure, Systems, and Components
V & V	Verification and Validation

References

1. International Atomic Energy Agency. *World Nuclear Performance Report 2019*; Report No. 2019/007; International Atomic Energy Agency: Vienna, Austria, 2019.
2. Rachamin, R.; Fridman, E.; Galperin, A. Feasibility assessment of the once-through thorium fuel cycle for the PTVM LWR concept. *Ann. Nucl. Energy* **2015**, *85*, 1119–1130. [[CrossRef](#)]
3. Xu, H. Improvement of PWR (LOCA) Safety Analysis Based on PKL Experimental Data. Ph.D. Thesis, Karlsruhe Technology of Institute, Karlsruhe, Germany, 2020.
4. International Atomic Energy Agency. *Defence in Depth in Nuclear Safety*; Report No. INSAG-10; International Atomic Energy Agency: Vienna, Austria, 1996.
5. International Nuclear Safety Advisory Group. *Basic Safety Principles for Nuclear Power Plants: 75-INSAG-3 Rev. 1*; Report No. INSAG-12; International Atomic Energy Agency: Vienna, Austria, 1999.
6. Lim, J.; Kim, H.; Park, Y. Review of the regulatory periodic inspection system from the viewpoint of defense-in-depth in nuclear safety. *Nucl. Eng. Technol.* **2018**, *50*, 997–1005. [[CrossRef](#)]
7. Nuclear Energy Institute. *B.5.b Phase 2&3 Submittal Guideline*; NEI 06-12 (Revision 3); Nuclear Energy Institute: Washington, DC, USA, 2009.
8. Xu, H.; Zhang, B.; Liu, Y. New safety strategies for nuclear power plants: A review. *Int. J. Energy Res.* **2021**, *45*, 11564–11588. [[CrossRef](#)]
9. Nuclear Energy Institute. *Diverse and Flexible Coping Strategies (FLEX) Implementation Guide*; NEI 12-06 (Draft Revision 0); Nuclear Energy Institute: Washington, DC, USA, 2012.
10. Nuclear Energy Institute. *Diverse and Flexible Coping Strategies (FLEX) Implementation Guide*; NEI 12-06 (Revision 5), ML18120A300; Nuclear Energy Institute: Washington, DC, USA, 2018.
11. Xu, H.; Zhang, B. A review on the Defense-in-Depth concept and the FLEX strategies in different countries after Fukushima accident. *Nucl. Technol. Radiat. Prot.* **2021**, *36*, 116–127. [[CrossRef](#)]
12. International Atomic Energy Agency. *Safety of Nuclear Power Plants: Design*; IAEA Safety Standards Series No. SSR-2/1 (Rev. 1); IAEA: Vienna, Austria, 2016.
13. International Atomic Energy Agency. *Deterministic Safety Analysis for Nuclear Power Plants*; IAEA Safety Standards Series No. SSG-2 (Rev. 1); IAEA: Vienna, Austria, 2019.
14. International Atomic Energy Agency. *Accident Management Programmes for Nuclear Power Plants*; IAEA Safety Standards Series No. SSG-54; IAEA: Vienna, Austria, 2019.
15. Xu, H.; Zhang, B. A review of the FLEX strategy for nuclear safety. *Nucl. Eng. Des.* **2021**, *382*, 111396. [[CrossRef](#)]

16. Webster, W.E., Jr. *U.S. Industry Response to the Fukushima Daiichi Nuclear Accident*; Institute of Nuclear Power Operations: Atlanta, GA, USA, 2012.
17. International Atomic Energy Agency. *Safety of Nuclear Power Plants: Design*; Specific Safety Requirements, No. SSR-2/1; International Atomic Energy Agency: Vienna, Austria, 2012.
18. U.S. Nuclear Regulatory Commission. *Standard Review Plan*; NUREG-0800, ML092330826; U.S. Nuclear Regulatory Commission: Rockville, MD, USA, 2007.
19. Fujioka, B.; Hirokawa, N.; Taniguchi, D. Probabilistic Assessment of Countermeasures for Loss of Ultimate Heat Sink to Spent Fuel Pool. In Proceedings of the 25th International Conference on Nuclear Engineering (ICONE25), Shanghai, China, 2–6 July 2017.
20. Hwang, S.H.; Seo, D.U.; Jung, S.I.; Kim, N.S.; Kim, Y.I. Long Term Core Cooling Analysis on Loss of Ultimate Heat Sink for APR1400. In Proceedings of the Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, 17–19 May 2017.
21. Gjorgiev, B.; Volkanovski, A.; Sansavini, G. Improving nuclear power plant safety through independent water storage systems. *Nucl. Eng. Des.* **2017**, *323*, 8–15. [\[CrossRef\]](#)
22. Nuclear Energy Institute. *Enhancements to Emergency Response Capabilities for Beyond Design Basis Events and Severe Accidents*; NEI 13-06, Revision 1; Nuclear Energy Institute: Washington, DC, USA, 2016.
23. Xu, H.; Badea, A.F.; Cheng, X. Sensitivity analysis of thermal-hydraulic models based on FFTBM-MSM two-layer method for PKL IBLOCA experiment. *Ann. Nucl. Energy* **2020**, *147*, 107732. [\[CrossRef\]](#)
24. Xu, H.; Badea, A.F.; Cheng, X. Analysis of two phase critical flow with a non-equilibrium model. *Nucl. Eng. Des.* **2021**, *372*, 110998. [\[CrossRef\]](#)
25. Xu, H.; Badea, A.F.; Cheng, X. Development of a new full-range critical flow model based on non-homogeneous non-equilibrium model. *Ann. Nucl. Energy* **2021**, *158*, 108286. [\[CrossRef\]](#)
26. Xu, H.; Zhang, P.; Zhou, Z. IVR model study for passive PWR. In Proceedings of the 20th International Conference on Nuclear Engineering and the ASME 2012 Power Conference (ICONE20-POWER2012), Anaheim, CA, USA, 30 July–3 August 2012.
27. Xu, H. Study on Mitigation Strategy of AP1000 Spent Fuel Pool Exterior Disaster. *At. Energy Sci. Technol.* **2012**, *46*, 473–478.
28. Xu, H.; Li, G. Research on key technical requirements for the FLEX strategy development. In Proceedings of the Conference of NPIC FLEX Project, Chengdu, China, 25 November 2020.
29. Xu, H.; Tang, T.; Zhang, B.; Liu, Y. Application of Artificial Neural Network for the Critical Flow Prediction of Discharge Nozzle. *Nucl. Eng. Technol.* **2021**, *54*, 834–841. [\[CrossRef\]](#)
30. Takada, T.; Itoi, T.; Hida, T.; Muramatsu, K.; Muta, H.; Furuya, O.; Minagawa, K.; Yamano, H.; Nishida, A. Development of Seismic Countermeasures Against Cliff Edges for Enhancement of Comprehensive Safety of NPPs—Part 1: Conceptual Study on Identification and Avoidance of Cliff Edges of NPPs Against Earthquakes. In Proceedings of the SMiRT-24, Busan, Korea, 20–25 August 2017.
31. Omoto, A. *Where Was the Weakness in Application of Defense-in-Depth Concept and Why? Reflections on the Fukushima Daiichi Nuclear Accident*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 131–164.
32. Schmitt, K.A. Function Allocation in Complex Socio-Technical Systems: Procedure Usage in Nuclear Power and the Context Analysis Method for Identifying Design Solutions (CAMIDS) Model. Ph.D. Thesis, Florida Institute of Technology, Melbourne, FL, USA, 2013.
33. U.S. Nuclear Regulatory Commission. 10 CFR Parts 50 and 52. *Fed. Regist.* **2015**, *80*, 70610–70647.
34. Canadian Nuclear Safety Commission. *Nuclear Research Trends Post-Fukushima*; Final Report, RSP-0292; Canadian Nuclear Safety Commission: Ottawa, ON, Canada, 2013.
35. Rumelt, R.P.; Schendel, D.; Teece, D.J. Strategic management and economics. *Strateg. Manag. J.* **1991**, *12*, 5–29. [\[CrossRef\]](#)
36. Patterson, E.A.; Taylor, R.J.; Bankhead, M. A framework for an integrated nuclear digital environment. *Prog. Nucl. Energy* **2016**, *87*, 97–103. [\[CrossRef\]](#)
37. Ashley, S.F.; Vaughan, G.J.; Nuttall, W.J.; Thomas, P.J. Considerations in relation to off-site emergency procedures and response for nuclear accidents. *Process Saf. Environ. Prot.* **2017**, *112*, 77–95. [\[CrossRef\]](#)
38. Vayssier, G.; Lutz, B. Lessons From SAMG Exercises for Existing and New Reactors. Topical Issues in Nuclear Installation Safety, Safety Demonstration of Advanced Water Cooled Nuclear Power Plants. In Proceedings of the International Conference, Vienna, Austria, 6–9 June 2017.
39. O'Brien, J. Beyond Design Basis Event Pilot Evaluations at US Department of Energy Nuclear Facilities. *Trans. Am. Nucl. Soc.* **2013**, *108*, 562–564.
40. Caro, R.J. CAE—The Spanish Emergency Support Center: A Centralized and Shared Emergency Support Service for Beyond Design Basis Events. *J. Nucl. Eng. Radiat. Sci.* **2016**, *2016*, 044504. [\[CrossRef\]](#)
41. Caro, R.J. Enhancements to Emergency Preparedness and Response in Spain. *Int. Nucl. Saf. J.* **2016**, *5*, 88–99.
42. Lee, Y.H. Current Status and Issues of Nuclear Safety Culture. *J. Ergon. Soc. Korea* **2016**, *35*, 247–261. [\[CrossRef\]](#)
43. International Atomic Energy Agency. *IAEA Safety Series 75-INSAG-3: Basic Safety Principles for Nuclear Power Plants*; International Atomic Energy Agency: Vienna, Austria, 1988.
44. International Atomic Energy Agency. *IAEA Safety Series 75-INSAG-4: Safety Culture*; International Atomic Energy Agency: Vienna, Austria, 1991.
45. Tronea, M.; Ciurea, C. Nuclear safety culture attributes and lessons to be learned from past accidents. *Int. Nucl. Saf. J.* **2014**, *3*, 1–7.

46. Farcasiu, M.; Nitoi, M. Requirements to amend the main influence factors on the safety culture after Fukushima accident. In Proceedings of the Annual International Conference on Sustainable Development through Nuclear Research and Education, Pitesti, Romania, 27–29 May 2015.
47. Westinghouse Electric Company. *Implementation of FLEX Equipment in Plant-Specific PRA Models*; PWROG-14003-NP; Westinghouse Electric Company: Pittsburgh, PA, USA, 2016.
48. Kim, I.S.; Kim, B.G.; Choi, D.I.; Lee, E.C. Incorporating MACST Mitigation Strategies into PSA Models: HRA and Data Issues. In Proceedings of the Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, 25–27 October 2017.
49. Eide, S.A. Historical perspective on failure rates for US commercial reactor components. *Reliab. Eng. Syst. Saf.* **2003**, *80*, 123–132. [\[CrossRef\]](#)
50. O'Connor, A.; Mosleh, A. A general cause based methodology for analysis of common cause and dependent failures in system risk and reliability assessments. *Reliab. Eng. Syst. Saf.* **2016**, *145*, 341–350. [\[CrossRef\]](#)
51. Harter, R. Beyond Design Bases Event Response: FLEX. In Proceedings of the IAEA Workshop on the Development of SAMGs Using the IAEA's SAMG Development Toolkit, Vienna, Austria, 11–15 December 2017.
52. Schumock, G.; Zhang, S.; Farshadmanesh, P.; Owens, J.G.; Kasza, N.; Stearns, J.; Sakurahara, T.; Mohaghegh, Z. Integrated Risk-Informed Design (I-RID) methodological framework and computational application for FLEX equipment storage buildings of Nuclear Power Plants. *Prog. Nucl. Energy* **2020**, *120*, 103186. [\[CrossRef\]](#)
53. Cordelle, F.; Champ, M.; Pochard, R. Primary break with total loss of high pressure safety injection. In Proceedings of the ENS/ANS International Conference on Thermal Reactor Safety, Avignon, France, 2–7 October 1988.
54. Bui, H.; Sakurahara, T.; Pence, J.; Reihani, S.; Kee, E.; Mohaghegh, Z. An Algorithm for Enhancing Spatiotemporal Resolution of Probabilistic Risk Assessment to Address Emergent Safety Concerns in Nuclear Power Plants. *Reliab. Eng. Syst. Saf.* **2019**, *185*, 405–428. [\[CrossRef\]](#)
55. U.S. Nuclear Regulatory Commission. 10 CFR Parts 50 and 52 Mitigation of Beyond-Design-Basis Events. *Fed. Regist.* **2019**, *84*, 154.
56. Nuclear Energy Agency. *Accident Management Insights after the Fukushima Daiichi NPP Accident*; NEA/CNRA/R(2014)2; Organization for Economic Co-Operation and Development: Paris, France, 2014.
57. Oh, D.Y.; No, H.C. Instrument failure detection and estimation methodology for the nuclear power plant. *IEEE Trans. Nucl. Sci.* **1990**, *37*, 21–30. [\[CrossRef\]](#)
58. Xu, H.; Tang, T.; Zhang, B.; Liu, Y. Identification of two-phase flow regime in the energy industry based on modified convolutional neural network. *Prog. Nucl. Energy* **2022**, *147*, 104191. [\[CrossRef\]](#)
59. Yadav, V.; Hansen, J.K.; Germain, S.S.; Christina, R. *Risk and Cost Analysis of Utilizing FLEX Equipment for O&M Cost Reduction in Nuclear Power Plants*; INL/EXT-18-51531; Idaho National Laboratory: Idaho Falls, ID, USA, 2018.
60. Yadav, V.; Biersdorf, J. *Utilizing FLEX Equipment for O&M Cost Reduction in Nuclear Power Plants*; INL/EXT-19-55445; Idaho National Laboratory: Idaho Falls, ID, USA, 2019.
61. Tavares de Sousa, J.R.; Diab, A. A Systems Engineering Approach for Uncertainty Analysis of a Station Blackout Scenario. *J. Korea Soc. Syst. Eng.* **2019**, *15*, 51–59.
62. Wang, Q.; Chen, X.; Xu, Y. Accident like the Fukushima unlikely in a country with effective nuclear regulation: Literature review and proposed guidelines. *Renew. Sustain. Energy Rev.* **2013**, *17*, 126–146. [\[CrossRef\]](#)
63. Kichline, M. Human reliability analysis for using portable equipment [presentation]. In Proceedings of the United States Nuclear Regulatory Commission, EPRI HRA for FLEX Workshop, Washington, DC, 28 February–1 March 2018.
64. Compare, M.; Baraldi, P.; Bani, I.; Zio, E.; McDonnell, D. Industrial Equipment Reliability Estimation: A Bayesian Weibull Regression Model with Covariate Selection. *Reliab. Eng. Syst. Saf.* **2020**, *200*, 106891. [\[CrossRef\]](#)
65. Dermar, F. Human and organizational considerations in severe accident management. In *IAEA International Experts' Meeting on Severe Accident Management in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant*; International Atomic Energy Agency: Vienna, Austria, 2014.
66. Zhou, D. Introduction to Seismic Mitigating Strategies Assessment (MSA) for BDBEE. 2016. Available online: <http://www.chns.org/index.php/2017-04-04-09-16-38/194-flex2016-materials> (accessed on 6 September 2016).
67. Yu, Y.; Zhao, B.; Yu, X.L. An Integrated EDMG to Deal With Extensive Damage for NPPs in China. In Proceedings of the 2017 25th International Conference on Nuclear Engineering (ICONE25), Shanghai, China, 2–6 July 2017.
68. Miller, C.; Cabbage, A.; Dorman, D.; Grobe, J.; Holahan, G.; Sanfilippo, N. *Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Dai-Ichi Accident*; SECY-11-0093, ML111861807; United States Nuclear Regulatory Commission: Washington, DC, USA, 2011.
69. Vayssier, G. Present Day EOPS and SAMG—Where Do We Go from Here? *Nucl. Eng. Technol.* **2012**, *44*, 225–236. [\[CrossRef\]](#)
70. Chang, J.; Xing, J. The General Methodology of an Integrated Human Event Analysis System (IDHEAS) for Human Reliability Analysis Method Development. In Proceedings of the 13th International Conference on Probabilistic Safety Assessment, and Management (PSAM 13), Seoul, Korea, 2–7 October 2016.
71. Nuclear Energy Institute. *Crediting Mitigating Strategies in Risk-Informed Decision Making*; NEI 16-06, (Revision 0), ML16286A297; Nuclear Energy Institute: Washington, DC, USA, 2016.
72. Queral, C.; Gómez-Magán, J.; París, C.; Rivas-Lewicky, J.; Sánchez-Perea, M.; Gil, J.; Mula, J.; Meléndez, E.; Hortal, J.; Izquierdo, J.M.; et al. Dynamic event trees without success criteria for full spectrum LOCA sequences applying the integrated safety assessment (ISA) methodology. *Reliab. Eng. Syst. Saf.* **2018**, *171*, 152–168. [\[CrossRef\]](#)

73. París, C.; Queral, C.; Mula, J.; Gómez-Magán, J.; Sánchez-Perea, M.; Meléndez, E.; Gil, J. Quantitative Risk Reduction by Means of Recovery Strategies. *Reliab. Eng. Syst. Saf.* **2019**, *182*, 13–32. [\[CrossRef\]](#)
74. Na, J.H. *KHNP's Strategies for Multi-Unit Extreme Hazards Response*; Safety Technology Center Central Research Institute, KHNP: Seoul, Korea, 2018.
75. Kim, S.C.; Park, J.S.; Chang, D.J.; Kim, D.H.; Lee, S.W.; Lee, Y.J. Development of an Evaluation Methodology for Loss of Large Area induced from Extreme Events with malicious origin. *J. Energy* **2016**, *65*, 12–20. [\[CrossRef\]](#)
76. Smith, C.L.; Vedros, K.; Kvarfordt, K.J. *Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE) Version 8 Volume 3 Users' Guide*; INL/EXT-09-17011; Idaho National Laboratory: Idaho Falls, ID, USA, 2011.
77. Zhang, S.; Ma, Z.G. Incorporating FLEX Strategies in Multi-Unit Probabilistic Risk Assessment. In Proceedings of the 2020 28th International Conference on Nuclear Engineering (ICONE28), Virtual, Online, 4–5 August 2020.
78. Guarnieri, F.; Travadel, S. Engineering thinking in emergency situations: A new nuclear safety concept. *Bull. At. Sci.* **2014**, *70*, 79–86. [\[CrossRef\]](#)
79. Kim, Y.; Park, J.; Jung, W. A classification scheme of erroneous behaviors for human error probability estimations based on simulator data. *Reliab. Eng. Syst. Saf.* **2017**, *163*, 1–13. [\[CrossRef\]](#)
80. Lim, H.K. A Conceptual comparative study of FLEX strategies to cope with Extended Station Blackout (SBO). In Proceedings of the 14th International Topical Meeting on Probabilistic Safety Assessment and Management (PSAM14), Los Angeles, CA, USA, 16–21 September 2018.
81. Electric Power Research Institute. *Incorporating Flexible Mitigation Strategies into PRA Models, Phase 1: Gap Analysis and Early Lessons Learned*; 3002003151; Electric Power Research Institute: Washington, DC, USA, 2014.
82. Kim, J.; Jung, W.; Park, J. Human Reliability Analysis of the FLEX/MACST Actions deploying Portable Equipment. In Proceedings of the Transactions of the Korean Nuclear Society Autumn Meeting, Yeosu, Korea, 25–26 October 2018.
83. Kim, J.; Cho, J. Technical Challenges in Modeling Human and Organizational Actions under Severe Accident Conditions for Level 2 PSA. *Reliab. Eng. Syst. Saf.* **2020**, *194*, 106239. [\[CrossRef\]](#)
84. Xing, J.; Kichline, M.; Hughey, J.; Humberstone, M. *Applying HRA to FLEX—Expert Elicitation Volume 1*. U.S.; RIL 2020-13, ML20345A318; Nuclear Regulatory Commission: Washington, DC, USA, 2020.
85. Cooper, S.; Franklin, C. *Applying HRA to FLEX—Using IDHEAS-ECA Volume 2*. U.S.; RIL 2020-13, ML21032A119; Nuclear Regulatory Commission: Washington, DC, USA, 2020.
86. Suh, Y.A.; Kim, J.; Park, S.Y. Time uncertainty analysis method for level 2 human reliability analysis of severe accident management strategies. *Nucl. Eng. Technol.* **2021**, *53*, 484e497. [\[CrossRef\]](#)
87. Lee, H.; Choi, W.; Kim, S.J. Sensitivity Analysis at the Time of MACST Action in Severe Accidents caused by Station Black Out (SBO). In Proceedings of the Transactions of the Korean Nuclear Society Virtual Spring Meeting, Virtual, 9–10 July 2020.
88. Shah, A.U.A.; Christian, R.; Kim, J.; Kang, H.G. Coping Time Analysis for Chromium Coated Zircaloy for Station Blackout Scenario based on Dynamic Risk Assessment. In Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference, Venice, Italy, 1–6 November 2020.
89. Park, J.; Arigi, A.M.; Kim, J. Treatment of human and organizational factors for multi-unit HRA: Application of SPAR-H method. *Ann. Nucl. Energy* **2019**, *132*, 656–678. [\[CrossRef\]](#)
90. Mancuso, A.; Compare, M.; Salo, A.; Zio, E. Portfolio optimization of safety measures for reducing risks in nuclear systems. *Reliab. Eng. Syst. Saf.* **2017**, *167*, 20–29. [\[CrossRef\]](#)
91. Smith, C.L. Risk-Informed Incident Management for Nuclear Power Plants. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2002.
92. Rahni, N.; Raimond, E.; Jan, P.; Lopez, J.; Löffler, H.; Mildenerberger, O.; Kubicek, J.; Vitazkova, J.; Ivanov, I.; Groudev, P.; et al. *Guidance on the Verification and Improvement of SAM Strategies with L2 PSA*; Technical Report ASAMPSA_E/WP40/D40.5/2016-05; IRSN: Fontenay-aux-Roses, France, 2016.
93. Karamzadeh, S.; Abdullah, S.M.; Manaf, A.A.; Zamani, M.; Hooman, A. An overview of principal component analysis. *J. Signal Inf. Process.* **2013**, *4*, 173. [\[CrossRef\]](#)
94. Wang, Z.; Pedroni, N.; Zentner, I.; Zio, E. Seismic fragility analysis with artificial neural networks: Application the nuclear power plant equipment. *Eng. Struct.* **2018**, *162*, 213–225. [\[CrossRef\]](#)
95. Nielsen, T.D.; Jensen, F.V. *Bayesian Networks and Decision Graphs*; Springer: New York, NY, USA, 2009.
96. Ma, Z.; Smith, C.; Prescott, S. A simulation-based dynamic approach for external flooding analysis in nuclear power plants. In Proceedings of the 20th Pacific Basin Nuclear Conference; Springer: Singapore, 2017.
97. Tabadar, Z.; Ansarifara, G.R.; Pirouzmand, A. Probabilistic safety assessment of portable equipment applied in VVER1000/V446 nuclear reactor during loss of ultimate heat sink accident for stress test program development. *Prog. Nucl. Energy* **2019**, *117*, 103101. [\[CrossRef\]](#)
98. Tabadar, Z.; Ansarifara, G.R.; Pirouzmand, A. Thermal-hydraulic modeling for deterministic safety analysis of portable equipment application in the VVER-1000 nuclear reactor during loss of ultimate heat sink accident using RELAP5/MOD3.2 code. *Ann. Nucl. Energy* **2019**, *127*, 53–67. [\[CrossRef\]](#)
99. Coleman, J.; Sabharwal, P. Seismic Risk Management Solution for Nuclear Power Plants. *Public Interest Rep.* **2014**, *67*.
100. Campbell, R.D.; Hardy, G.S.; Ravindra, M.K.; Johnson, J.J.; Hoy, A.J. Seismic re-evaluation of nuclear facilities worldwide: Overview and status. *Nucl. Eng. Des.* **1998**, *182*, 17–34. [\[CrossRef\]](#)

101. Kobare, S.K.; Kafka, P. Expert systems for emergency alarms analysis during accident situations in nuclear reactors. *Reliab. Eng. Syst. Saf.* **1992**, *37*, 139–149. [\[CrossRef\]](#)
102. Zubair, M.; Amjad, Q.M.N. Calculation and updating of Common Cause Failure unavailability by using alpha factor model. *Ann. Nucl. Energy* **2016**, *90*, 106–114. [\[CrossRef\]](#)
103. Farmer, M.T. *Reactor Safety Technologies Pathway Technical Program Plan*; INL/EXT-11-23452; U.S. Department of Energy: Washington, DC, USA, 2017.
104. Kim, J.; Park, S.Y.; Ahn, K.I.; Yang, J.E. iROCS: Integrated accident management framework for coping with beyond-design-basis external events. *Nucl. Eng. Des.* **2016**, *298*, 1–13. [\[CrossRef\]](#)
105. Kim, I.S.; Choi, Y.; Jeong, K.M. A new approach to quantify safety benefits of disaster robots. *Nucl. Eng. Technol.* **2017**, *49*, 1414–1422. [\[CrossRef\]](#)
106. Yoshida, T.; Nagatani, K.; Tadokoro, S.; Nishimura, T.; Koyanagi, E. Improvements to the Rescue Robot Quince Toward Future Indoor Surveillance Missions in the Fukushima Daiichi Nuclear Power Plant. In *Field and Service Robotics*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 19–32.
107. Asama, H. Utilization of Robot Technology for Accident Response and Decommissioning of Fukushima Daiichi Nuclear Power Station. *J. Jpn. Soc. Mech. Eng.* **2014**, *117*, 648–651.
108. Vayssier, G. Accident management under extreme events. *Int. J. Perform. Eng.* **2014**, *10*, 669–680. [\[CrossRef\]](#)
109. Wybo, J.L.; Kowalski, K.M. Command centers and emergency management support. *Saf. Sci.* **1998**, *30*, 131–138. [\[CrossRef\]](#)
110. Greene, S.R. Nuclear Power and Electric Grid Resilience: Current Realities and Future Prospects. Ph.D. Thesis, University of Tennessee, Knoxville, TN, USA, 2018.
111. Vayssier, G. Accident management under extreme events. *J. Energy* **2016**, *65*, 21–31. [\[CrossRef\]](#)
112. Duffey, R.B. Dynamic Theory of Losses in Warfare. *Eur. J. Oper. Res.* **2017**, *261*, 1013–1027. [\[CrossRef\]](#)
113. Po, L.C.C. Conceptual Design of an Accident Prevention System for Light Water Reactors Using Artificial Neural Network and High-Speed Simulator. *Nucl. Technol.* **2020**, *206*, 505–513. [\[CrossRef\]](#)
114. Yang, Z.; Chen, Y.; Luo, H. Research and Development of Validation and Drill System for Full Scope of Severe Accident Management Guideline. *J. Nucl. Eng. Radiat. Sci.* **2017**, *2017*, 041011. [\[CrossRef\]](#)
115. Luo, H. *PSA-HD User Guide*. UG PSA-HD; GSE Power Systems, Inc.: Sykesville, MD, USA, 2013; p. 6.