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A REVIEW ON THE DEFENSE-IN-DEPTH CONCEPT AND THE FLEX STRATEGIES IN DIFFERENT COUNTRIES AFTER FUKUSHIMA ACCIDENT

by

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Review paper
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To enhance the defense in depth for nuclear safety after the Fukushima nuclear accident, the U.S. Nuclear Energy Institute put forward the concept of diverse and flexible coping strategies and the corresponding FLEX support guidelines for the special scenarios of extended loss of alternating current power and loss of ultimate heat sink caused by beyond-design-basis external event. Subsequently, the idea of the FLEX strategy was broadly accepted and spread widely. The introduction of the concept of FLEX strategy into the defense in depth was the biggest improvement for nuclear safety in the recent decade. This paper has reviewed the concept of traditional defense in depth and its weakness that led to the Fukushima nuclear accident, which led to the development motivation for the FLEX strategy. The research progress of the FLEX strategy in different countries in the past ten years has been reviewed. Based on the literature, and the aforementioned review, some recommendations for future work have been presented.

Key words: diverse and flexible coping strategy, defense in depth, loss of ultimate heat sink, beyond-design-basis external event, extended loss of alternating current power, Fukushima nuclear accident

INTRODUCTION

According to the prediction of the International Atomic Energy Agency (IAEA), the demand for global primary energy will be an increment of about 2.5 times in 2050 comparing with the beginning of this century in 2000. Nuclear energy has the potential to contribute to a sustainable solution for the world's growing energy needs and also environmental problems [1]. After a slight decrease in nuclear generation around the Fukushima nuclear accident in 2011, the nuclear generation increased successively these years. The development of the world's nuclear industry currently faces economic, environmental, and safety concerns. The root of the concerns is nuclear safety [2].

Similar to most engineering systems, the safety of nuclear power plants (NPP) is the most critical concern. Nuclear engineering design is committed to maximizing nuclear safety. The NPP have been designed to withstand a large series of postulated initiating events, including design basis accidents (DBA) and design extension conditions (DEC) [3]. These two accidents may lead to severe accidents (SA) if they are not handled properly [4]. The DBA are postulated to establish the design bases of the safety systems, which are considered on the licensing basis. Representative DBA are main steam line break, loss-of-coolant accident, and so on [5]. The DEC were introduced with the purpose to further improve safety by enhancing NPP capability to withstand the conditions generated by accidents that are more severe than DBA [6]. Examples of DEC are station blackout, loss of ultimate heat sink (LUHS), and anticipated transient without scram [7].

To get the NPP license from the authority, the NPP design of the licensee offers a demonstrated protection using various safety and non-safety systems with application of emergency operating procedures (EOP) and severe accident management guidelines (SAMG) (if the EOP are not effective). The set of EOP and SAMG is designed based on scenarios, often using the deterministic thermal-hydraulic assessment [8, 9] and the probabilistic safety analysis (PSA) [10]. Based on the advanced design and improvement of safety procedures/guidelines, the core damage frequency and large early release frequency, which are the key safety criteria for NPP safety, became smaller and smaller.

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According to the safety requirements, the current NPP design can prevent core damage under DBA or DEC conditions. However, core damage can occur under beyond-design-basis external events (BDBEE), especially extremely severe external events like the east Japan great earthquake that led to the Fukushima nuclear accident and subsequent large radiation release [11]. To enhance the defense in depth (DID) for nuclear safety after that, 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). Subsequently, the idea of the FLEX strategy was broadly accepted and spread widely in the recent decade. Since 2021 is the 10^{th} anniversary of the Fukushima nuclear accident, the current progress, and the existing challenges of the FLEX strategy deserve a review, which is the main objective of this article.

DEFENSE-IN-DEPTH CONCEPT AND THE INTRODUCTION OF THE FLEX STRATEGY

This section presents a review of the concept of traditional DID and its weakness that led to the Fukushima nuclear accident, consequently the introduction of the FLEX strategy to enhance the DID for nuclear safety.

Defense in depth

Traditional DID

The main pillars for nuclear safety are based on the following concept as shown in fig. 1. At the beginning of this century, the IAEA published its revised fundamental safety principles, which importantly states that *the fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation* [12]. Consequently, the concept and methodology of DID were brought out at the end of the last century [13], and then it spread to regulatory agencies around the world.

Except for building four physical barriers [14] as shown in fig. 1 for accident prevention or mitigation, the fundamental idea for DID is to set several consecutive and independent levels of protection to prevent or mitigate the consequences of accidents [15]. The NPP conditions are divided into five levels – normal operation condition, AOO, DBA, SA, and post-SA situation - for different protections [16]. The definition of each condition could be found in the IAEA report [17]. The frequencies from AOO to post SA situation are decreased from around 10^{-2} per reactor-year to less than 10^{-6} per reactor-year. If one level of protection or barrier is to fail, the subsequent level or barrier would be available.

The concept of DID could be well understood in fig. 2. Each blue board represents a defense layer for hazard prevention. The ideal condition of DID is shown in fig. 2 as the case (a). They are perfect without any failure and therefore there is no possibility of system loss. But case (a) is unrealistic, which only exists in theory [18]. A more realistic situation is shown in fig. 2 as the case (b). There may be several holes on each blue board, which means failures in each layer of DID. The failures in the first layer may be prevented by the second layer. If both the first layer and the second layer are failures, losses may be prevented by the third layer, and so on, the failures are shown as lines-1 in fig. 2 case (b). According to the PSA, the probability of failure with

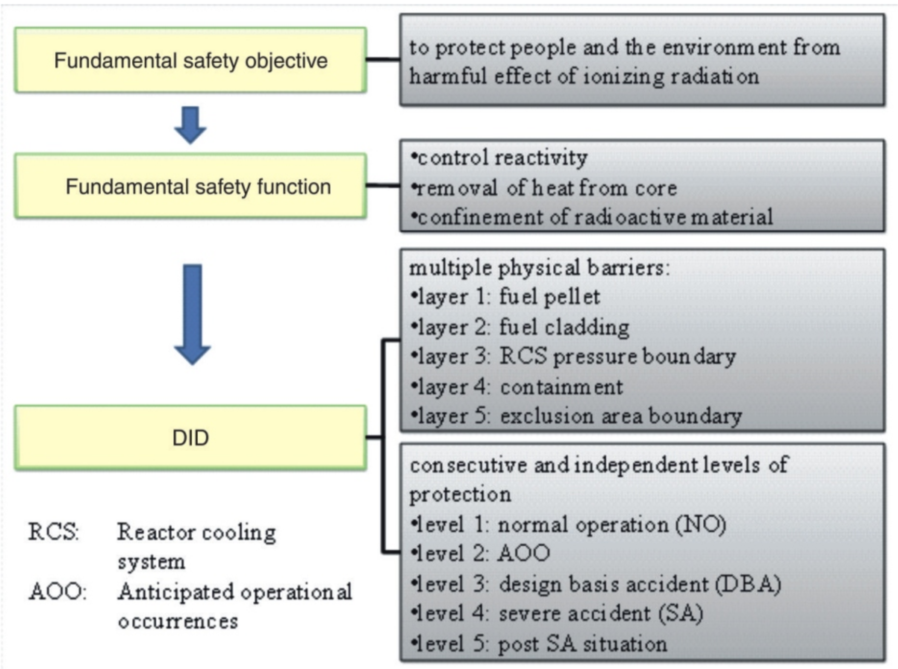

Figure 1. Nuclear safety concept

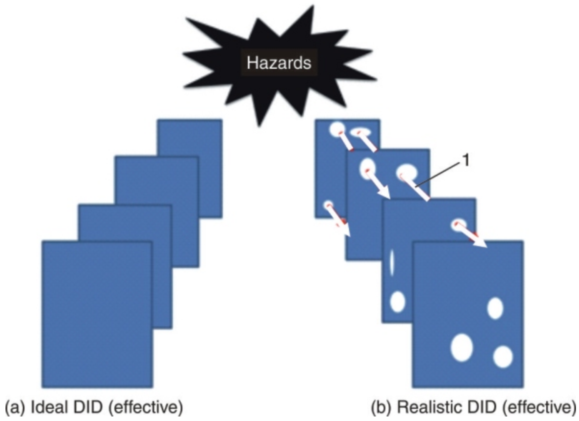

Figure 2. Traditional DID concept for hazards

more DID layers will decrease sharply when the layers increase [19]. Consequently, there is nearly no chance for all layers of failure based on the independence assumption of the layers.

Weakness of traditional DID – cliff-edge effect

However, the Fukushima nuclear accident showed some defects of the traditional DID for implementation and highlighted the possibility that extreme natural phenomena could challenge the prevention, mitigation, and emergency preparedness of the DID layers [20]. From the perspective of review currently, this seemingly perfect DID theory has a significant weakness that DID does not consider the cliff edge (CE) which leads to the so-called cliff-edge effect (CEE) in the viewpoint of probability theory [21]. The CE could be divided into two types, physical CE and knowledge-oriented CE, which will be defined and discussed separately as follows.

– according to the definition of [22], the physical CE represent the phenomenon that there occurs a significant increase of consequence due to a small amount of decrease of the occurrence frequency of the external event. This definition of CE can be understood as depicted in the risk curve, *i. e.*, a relationship between an occurrence probability and its consequence, as shown in fig. 3. An example of the physical CE is the common cause failure (CCF) brought by large external events [23]. To make matters worse, if the external event is BDBEE, it may impact multi-units in the same site or NPP in the same disaster area [24].
– Knowledge-oriented CE is associated with the knowledge limit within which we can deduce and make reliable decisions based on our certain amount of knowledge and available information of an objective of interest. These CE imply the deviation from the known domain to the unknown domain or phenomena unexpected. As an example, failure of containment may happen due to the unknown detailed mechanism of hydrogen detonation. As a result of knowledge-oriented CE, it may lead to inappropriate decisions, which may cause the failure of DID [25].

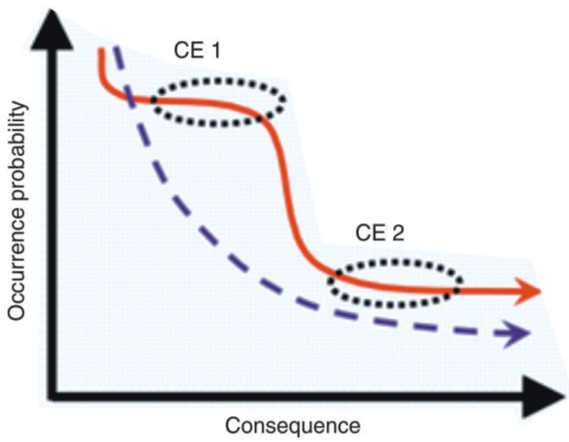

Figure 3. The CEE [22]

The concept of DID would be ineffective owing to CEE, as shown in fig. 4. The CCF (a kind of physical CE) may lead to failure of all layers of defense simultaneously or successively and consequently, leads to the failure of DID as shown in fig. 4(a). In fig. 4(b), although the hazard does not cause the original DID to fail completely, it may skip some layers of the DID system, as an example, the last layer in fig. 4(b), and as a result, lead to an unknown failure of the system.

Failure of DID in the Fukushima nuclear accident

To prevent such kinds of the accident like the Fukushima nuclear accident in the future, we need a way to reduce and avoid this kind of CE and enhance the concept of DID. After Fukushima nuclear accident, IAEA held a conference, which focused on DID issues and came to a summary about DID including:

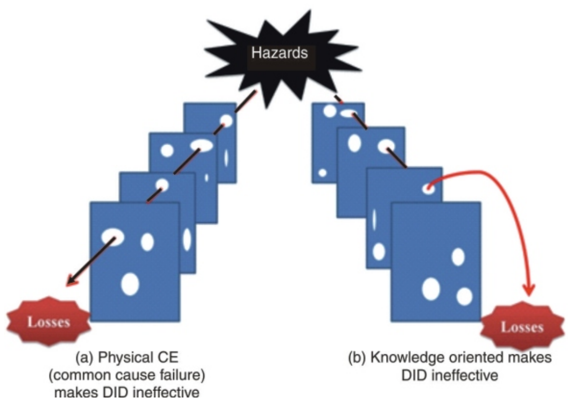

Figure 4. Failure of DID concept owing to CEE

- The DID has to be strengthened and extensively applied in order to meet the most recent safety objectives,
- further development and guidance are required for the strengthening measures, and
- criteria to choose between fixed and mobile equipment should be developed.

To prevent or mitigate the hazard caused by BDBEE, additional strategies were proposed for coping with these events including the utilization of portable equipment, permanent equipment, or combination of portable and permanent equipment. The FLEX strategy focuses on maintaining, enhancing, or restoring NPP key safety functions that address the potential consequences of these BDBEE. Cavaluzzi has used the PSA method to prove that FLEX strategies with portable equipment could decrease the possibility of failure during BDBEE [26].

The introduction of the FLEX strategy

The kind of natural disaster that caused the Fukushima nuclear accident was not considered plausible in the vicinity of any NPP in the USA. But the U.S. NRC established a near term task force (NTTF) to determine whether safety improvements should be recommended for US commercial NPP, which finally issued a report [27] including 12 recommendations in total. Apart from laws and formal regulations, this report named *Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Daiichi Accident* may be the single most influential document in the U.S. NRC history [28]. According to the different urgencies of the recommendations, the tasks were divided into 3 tiers as shown in fig. 5 [29].

In addition, many other organizations investigated the Fukushima nuclear accident after it happened, producing quite a lot of reports [30, 31]. Several researchers have reconsidered the lessons from Fukushima nuclear accident, which have been summarized here, as shown in fig. 6 [32, 33].

In the following year of the Fukushima nuclear accident, a further recommendation from NTTF was the U.S. NRC order EA-12-049 (issued on 12 March 2012) [34], requiring all U.S. NPP to implement mitigation strategies to protect against the scenario of Extended Loss of Alternating current (AC) Power (ELAP) caused by BDBEE. Consequently, U.S. NEI put forward the concept of FLEX and corresponding FSG specifically for external scenarios as the Fukushima nuclear accident, which use on-site or off-site replacement and substitute equipment, making connections and repairs, just like restoring power in any system [35]. Actually, the FLEX strategy may be considered as an extension of extensive damage mitigation guideline (EDMG), which was developed by U.S. NEI aiming at preventing or mitigating hazards caused by explosions or fires (especially these caused by man-made hazards such as aircraft attack) after the 911 terrorist attacks [36, 37]. Additionally, the concept of the FLEX strategy to use portable equipment to mitigate the accidents has already been adopted by IAEA (SSG-54), to deal with accidents, especially SA [38].

The strategy has been modified from draft revision 0 in 2012 to version 4 in 2016 [39] owing to its importance and urgency. In the last version of the NEI FLEX strategy report, the theory of FLEX strategy was supplemented with the shutdown modes analysis to identify and reduce the risk of showdown process, the *Appendix E* for

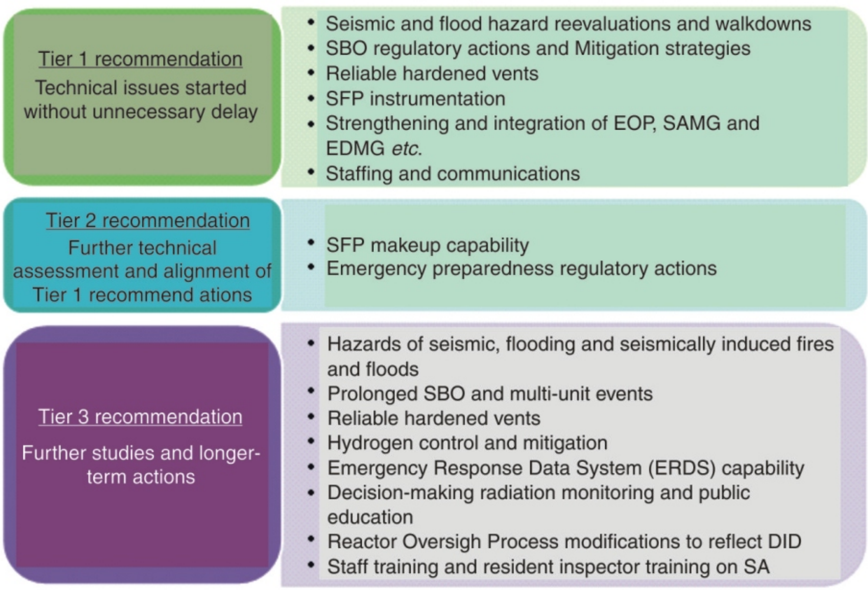

Figure 5. Three tiers of recommendations for enhancing reactor safety in the 21st century

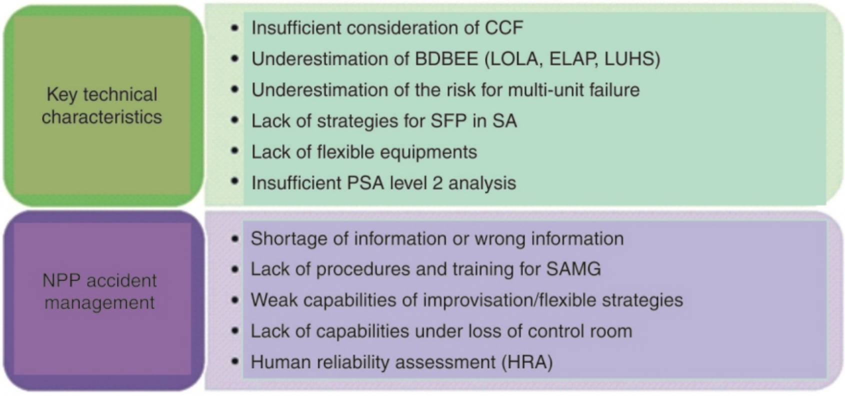

Figure 6. Lessons from Fukushima accident

validation guidance of FLEX strategy, the *Appendix G* and *Appendix H* for mitigating strategies assessment of new flood and seismic hazard information, respectively.

Based on the identified accident sequences following the BDBEE and CE at each NPP, the objective of the FLEX strategy is to improve the resilience and flexibility for prevention and mitigation strategies of NPP, and consequently enhancing the DID [40]. The concept of the FLEX strategy was accepted by the U.S. Nuclear Regulatory Commission (NRC) in August 2012 [41]. According to the afore-mentioned recommendations from literature and issues for the Fukushima nuclear accident, and the characteristic of the FLEX strategy, the capabilities of the FLEX strategy could be summarized here as shown in tab. 1.

The aim of the FLEX strategy implemented during the BDBEE is to decrease the failure risk of NPP as low as possible. To achieve this objective, the FLEX strategy should be implemented to achieve the following functions [42]:

– mitigation of the remaining residual risks (*i. e.*, the risks caused by physical CE (CCF), and
– prevention and/or mitigation of the unknown risk, (*i. e.*, the risks caused by knowledge-oriented CE).

Therefore, how the FLEX strategy enhances the concept of DID could be explained by fig. 7.

RESEARCH PROGRESS OF FLEX STRATEGY IN DIFFERENT COUNTRIES

After the Fukushima accident, the responses of different countries are quite different from each other in the aspect of government policy and utilities post-accident measures, as different countries have

Table 1. The capabilities of the FLEX strategy

Category	Subcategory	Content
Technical strategy	CCF	CCF for Multi-unit NPP site
	Initial BDBEE	– Seismic events
		– Flood
		– High winds
		– Extremely low temperatures (including snow, ice)
		– Extremely high temperatures
	Induced DEC	– LOLA
		– ELAP
		– LUHS
	Prevention and mitigation capability for SFP accident	– SFP makeup
		– SFP spray
		– SFP leak mitigation
	Phenomena of SA	– Containment venting
	Enhance NPP procedures/guidelines	Strengthening and integration of NPP EOP / SAMG strategy for beyond design basis accidents (BDBA)
Management strategy	Personnel management	– Staffing
		– Training and drilling
		– Communications
		– Human reliability assessment
	Resource management	On-site and off-site resource protection and deployment

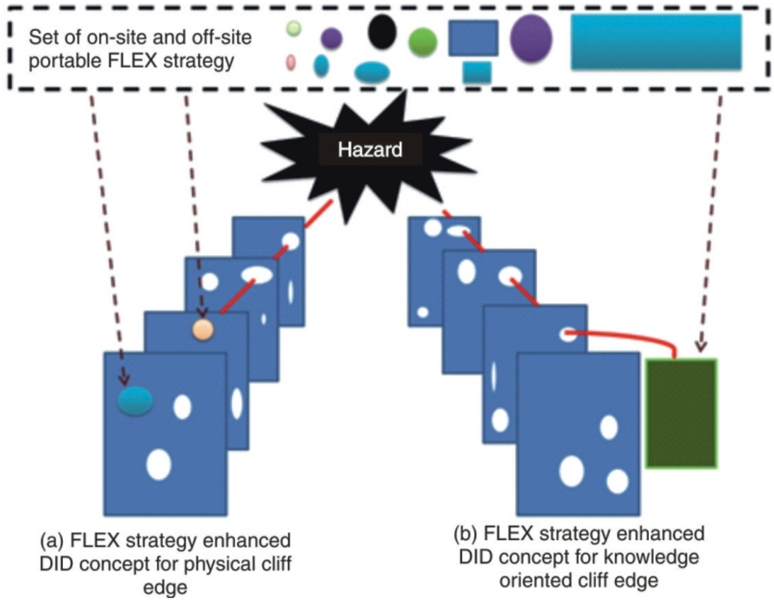

Figure. 7. The FLEX strategy enhanced DID concept

different national conditions and attitudes towards nuclear energy [28]. However, many countries now have decided to have portable equipment available for added capability, and there is considerable worldwide interest and research effort directed toward FLEX strategy, especially in the countries with high-density NPP sites such as Korea, since the possibilities of BDBEE and its hazards at multi-unit sites are larger. In this section, introductions and comparisons of the post-Fukushima safety enhancement measures related to FLEX (or similar to the concept of FLEX but with different nomenclatures) in different countries are described according to the available literature. It should be noted that even if similar concepts or actions are adopted in different countries, they have different nomenclatures. Additionally, this section mainly focuses on the regulatory requirements in observed countries and the response from their nuclear industries briefly since the FLEX strategy is site-specific and different NPP developed their own detailed strategies, which are dissimilar from each other. For more detailed information about the FLEX strategies at a specific NPP site, the corresponding reference can be resorted to.

USA

Following the Fukushima accident, the U.S. NPP assessed the safety items and concluded that BDBEE (*e. g.*, seismic events, external flooding, *etc.*) are highly unlikely but could present challenges to NPP. The Fukushima Response Steering Committee, a leadership structure formed to integrate and co-ordinate the industry's ongoing response to the Fukushima nuclear accident, developed the FLEX concept. The committee – senior electric utility executives, reactor owners' groups, the Nuclear Energy Institute (NEI), the Institute of Nuclear Power Operations, and the Electric Power Research Institute-spent the year following Fukushima ensuring that its lessons are fully understood and integrated into plans to enhance safety.

Numerous industry activities related to NPP procedures/guidelines were initiated to implement lessons learned in the USA [43]. In addition to updating the generic EOP/SAMG strategy, the usage of EDMG and FLEX equipment has attracted much attention [44]. The integration of the updated EOP/SAMG strategy with EDMG, FSG, and emergency mitigating equipment guidelines (EMEG) is an essential part of the activities.

After the FLEX strategy had been developed by NEI, all U.S. NPP had to develop FLEX strategies to protect against ELAP resulting from BDBEE and submit an *overall integrated plan*. These so-called FLEX integrated plans should have had to be submitted to the US regulator no later than two refueling cycles after submittal, or by end of 2016, whichever came first [45].

Under the FLEX program, NPP owners have invested heavily in additional on-site diesel generators and diesel-driven pumping systems. Efforts have been made to expand on-site diesel fuel storage capabilities. Several FLEX integrated plans could be resorted to for more detail, for example:

– Nuclear Innovation North America (NINA) reviewed the FLEX capabilities of the NPP at the South Texas Project Units 3 and 4 (STP3&4), which are the US-Advanced Boiling Water Reactors (ABWR) and concluded that the US-ABWR was capable of providing a significant coping period for an ELAP and consequent LUHS without core damage by using existing plant systems and considering also FLEX strategy [46].

– Fort Calhoun NPP established detailed flow charts in procedures/guidelines to introduce the FSG for different safety objectives in ELAP/LUHS scenarios. Simultaneously, a list of FLEX strategies was built to modify the *support optimal strategies* [47].
– Palo Verde NPP has checked the safety issues after the Fukushima nuclear accident and introduced the FLEX equipment, such as portable pumps, FLEX generators, condensate storage tanks,and the refueling water tank to enhance the safety systems in NPP [45].
– The 3-unit Browns Ferry NPP Authorized by the Tennessee Valley has the capacity to store at least 282, 240 gallons of diesel fuel on-site for its FLEX diesel generators [48].

Finally, the US NRC intended to issue a Safety Evaluation Report for each site following the demonstration of successful implementation of the FLEX plan.

Based on the summary of feedback experience and research on FLEX strategies after the Fukushima nuclear accident, the U.S. NRC proposed to amend Title 10 of the Code of Federal Regulations (10 CFR). The new rules were finally issued in August 2019 [49], with the following emphasized key points and requirements of FLEX strategies for each applicant or licensee:
– build the integrated response capability that includes FSG, EDMG, and EOP,
– develop, implement, and maintain a supporting organizational structure with defined roles, responsibilities, and authorities for directing and performing the FSG and EDMG,
– develop, implement, and maintain sufficient staffing to support the implementation of FSG and EDMG in conjunction with the EOP during an event, and
– provide training, drills, or exercises to personnel that perform activities in accordance with FSG and EDMG.

The SAFER (short for Strategic Alliance for FLEX Emergency Response) team, an alliance established between AREVA and Pooled Inventory Management, is contracted by the U.S. nuclear industry to establish and operate National SAFER Response Centers to purchase, store, maintain and deliver emergency response equipment in the case of a major nuclear accident or BDBEE in the U.S. [50]. Two SAFER control centers were built in Lynchburg and Birmingham separately. Additionally, two regional response centers Memphis and Phoenix (also called FLEX support centers) have been built with equipment, logistic, and support technicians for the deployment of off-site FLEX strategies within 24 hours [51].

The NRC also emphasizes that it is allowed for a licensee to make changes to FSG and EDMG without prior NRC approval, provided that the licensee performs an evaluation demonstrating that regulatory requirements continue to be met. Documentation of all changes would need to be maintained.

In addition, the U.S. NRC has made efforts to credit FLEX strategies in regulatory applications [52], such as investigating human reliability assessment methods for the FLEX context [53], incorporating the FLEX equipment into PSA [54] and overseeing the licensee's implementation of FLEX strategies, preparing Regulatory Guide 1.226 to guide the licensees on how to demonstrate their compliance with regulations of BDBEE planning and preparedness.

Canada

Following the Fukushima nuclear accident, Canadian NPP procured equipment and initiated modifications to improve response capability for BDBA. Consequently, modified guidance was correspondingly introduced for these changes to address BDBA [55]. To prevent SA, emergency mitigating equipment are introduced as additional barriers for accident management, maintaining reactor core cooling, and protecting the integrity of containment in Canada. Hence, EMEG, which is similar to EDMG and FLEX, is being prepared in parallel with enhancements of SAMG by reflecting the lessons learned from the Fukushima nuclear accident [56].

From then on, the Canadian Nuclear Safety Commission regulatory document REGDOC-2.5.2 [57] requires the design authority to consider mitigation of a broad range of accidents and provide the initial accident response guidance including EMEG, which is robust, readily available, easily deployable within required timeframes, and has adequate redundancy [58].

European Union

The Fukushima nuclear accident triggered the need for coordinated action at the EU level to identify potential further improvements in NPP safety. The Council of the EU asked the European Commission and the European Nuclear Safety Regulators Group (ENSREG) to investigate the robustness of a plant for events beyond its licensed design basis and reassess the safety margins of NPP in the light of the events in Fukushima [59]. On 25th March 2011, ENSREG decided that the safety of all EU nuclear plants should be reviewed, based on comprehensive and transparent risk and safety assessments – the stress tests [60]. The stress tests consist of three main steps: a self-assessment by licensees, followed by an independent review by the national regulatory bodies, and by the third phase of international peer reviews. The international peer review phase consists of three steps: an initial desktop review, three topical reviews in parallel, and seventeen individual country peer reviews. Through the stress test, each specific plant could identify its weak points and any CEE by the postulated extreme natural events, and could further find any provisions to prevent these CEE or increase its robustness through modification of hardware or procedures/guidelines, organizational preparedness, *etc*. The FLEX strategies in France and Spain will be introduced following as examples of the EU.

France

Following the Fukushima nuclear accident, the French Nuclear Safety Authority asked the French nuclear licensees to carry out a reassessment of their facilities in the light of the Fukushima nuclear accident. These reassessments, called Complementary Safety Assessments, were based on the specifications attached to the aforementioned decisions and consistent with the specifications for the stress tests requested by the European Council. With the assessment results, France has shown that its nuclear facilities have a satisfactory level of safety. However, it had been decided to significantly improve their robustness to extreme situations, by introducing nuclear rapid response force (FARN), which has a similar objective and function to EDMG. In addition, some risk of CEE has been identified during the assessments, corresponding measures, which was called *hardened safety core* (HSC), similar to the FLEX strategy in the USA, have been developed, providing a set of material to enable the NPP to withstand hazards or situations caused by the CEE [61]. The HSC must ensure ultimate protection of nuclear facilities with the following three objectives:
- Prevent a SA or limit its progression,
- limit large-scale releases in the event of an accident which it was not possible to control, and
- enable the licensee to perform its emergency management duties [62].

The HSC may be composed of existing structures, systems, and components (SSC), that might require to be strengthened, or of new SSC that should be designed and sized to withstand extreme situations. The SSC may be active or passive. The implementation of HSC for operating NPP compensated for some weaknesses in the current approach and improved significantly the robustness of the installations against BDBEE [63].

Spain

After Fukushima nuclear accident, two complementary technical instructions (ITC) were issued by the Spanish Nuclear Safety Council: ITC-1 according to the European *stress tests*, and ITC-2 about the potential LOLA of NPP due to big explosions and fires. Based on the assessments of *stress tests*, the Spanish NPP confirmed the robustness of the Spanish nuclear fleet and proposed a series of improvements aimed at reinforcing the response to BDBEE, thus increasing safety margins [38]. Both EDMG and FLEX strategies have also been established in Spain for hazards caused by BDBEE.

A new Alternative Emergency Management Centre (in Spanish, CAGE) has been built at each one of the Spanish NPP. These new centers are designed to allow the management of the emergency in LOLA scenarios, which are independent and have the resources to deal with the proposed scenarios autonomously for 72 hours, providing protection to the intended personnel [37]. The emergency support service of CAGE aims to strengthen the NPP emergency capabilities, by integrating with the Emergency Response Organization of NPP. In addition, a common Emergency Support Center (CAE) has been established, sharing resources (such as portable diesel generators, portable diesel pumps) among the different Spanish NPP and capable of providing support in the event of an emergency at any of the sites. The CAE service is available to any Spanish NPP. The service can be activated at any time of day and any day of the year. Once activated, the CAE acts under the instructions of the Director of the Emergency Plan of the NPP that activates the service. The CAE mobilizes equipment and personnel to the NPP site, to respond to the request made in less than 24 hrs. after service activation. The operation can be summarized in three sequential stages: activation, mobilization, and deployment [51]. Additionally, a logistics company Carreras Logistics Group is operative and available for supporting any Spanish NPP in an emergency [64].

Korea

Stress tests were required for all the NPP after the Fukushima nuclear accident in the Republic of Korea. Regarding the BDBEE such as Earthquake and Tsunami, their induced loss of safety functions (ELAP + LUHS) and possible severe accident, Korea had divided the stress tests into 3 steps:
- Operator self-assessment,
- adequacy review of including plant walk-down and detailed reviews of the regulator by experts, and
- reviews of nuclear safety and security commission, which was launched on October 26, 2011, as a regulatory body directly under the President in charge of strengthening independence and nuclear safety [65].

Based on the stress tests, a total of 56 post-Fukushima action items were considered to enhance nuclear safety, such as the modification of structure and equipment design against BDBEE, the reinforcement of emergency response, *etc.* [66]. A centralized expert team called Severe Accident Fast Response Expert Team has been built at Korea Hydro and Nuclear Power Company. The team can be dispatched to the emergency site within 6hrs. from the company Central Research Institute in Daejeon to any NPP with disaster in Korea [67].

Furthermore, several advanced and detailed studies have been done in Korea, such as the study on FLEX in a multi-unit site during a BDBEE case [41], integrating EDMG and FLEX to provide comprehensive strategies for NPP [68], the introduction of an integrated passive safety system to achieve various passive functions for FLEX strategies in OPR1000 NPP [69], the introduction of humanoid robotics for nuclear disaster management [70].

Based on the afore-mentioned study, Korea revised the nuclear law in Jun 2016 that before June 2019 all operating NPP should submit accident management plans (AMP), which included not only EOP and SAMG but also EDMG and MACST operating guidelines [68]. The MACST means a multi-barrier accident coping strategy that is similar to the FLEX strategy of the USA.

China

Immediately after the Fukushima nuclear accident, China's State Council decided to perform a comprehensive safety inspection of the operating NPP and NPP under construction, and suspend the construction permit issuance process for new NPP. China's State Council required that specific measures should be designed against man-made/natural DBDEE, for example, malevolent airplane impact and external flooding. Additionally, the FLEX strategy shall be available to instruct the actions of the operator in such cases. Consequently, several studies related to FLEX strategies have been done for different NPP types in China. During the period of AP1000 technical transfer from Westinghouse to China, Xu *et al*. focused on in-vessel retention strategy [71] and its uncertainty [72] in an assumed SA to enhance the DID of AP1000 safety system. Xu [73] has also studied the EDMG/FLEX strategy for the SFP of AP1000 by using the on-site existed system, fire system, and portable devices. Xing and Wang [16] have concentrated on the FLEX strategy for the Hualong No. 1 (China's domestic state-of-the-art *Generation III* NPP and the first unit of Hualong No. 1 in the world was put into commercial operation on January 30, 2021). In Hongyanhe NPP (CPR1000) [74], the EDMG and FLEX strategies have been established. Additionally, related to FLEX development in China, Xu *et al*. [75, 76] have concentrated on the procedures to develop FLEX strategy based on the summary of the literature. Yu *et al.* [77] have built an integrated strategy which was divided into three parts for control and command, control room recovery, and accident management separately.

FUTURE WORK RECOMMENDATION

The FLEX strategy was proposed after the Fukushima nuclear accident. Many related studies could be found in the literature and it has developed significantly in the past ten years. But the current research is relatively preliminary and not systematic. It can be expected that there will be more FLEX strategy-related research in the future. Several research directions are proposed as follows:

- The BDBEE may impact all the plants on-site, multi-unit FLEX strategy needs to be considered in detail, not only from the aspect of technical issues but also the management.
- Some researchers began to consider the economical characteristic of the use of portable equipment/devices. But more detailed methodology needs to be established for quantitative analysis.
- Integration of the FLEX strategy has always been the focus of the FLEX strategy research, but so far it has not achieved a completed integration, and different countries have different understandings of integration. A more powerful strategy set for accident management needs to be built.
- A methodology for the on-site and *off-site* resource management (including the logistics) during a BDBEE scenario to improve their reliability should be developed to achieve a highly efficient intervention of the equipment/devices.

AUTHORS' CONTRIBUTIONS

Both of the authors made valuable contributions to this review work. H. Xu and B. Zhang both connected the literature, summarized the key points of each literature, and reviewed them. The manuscript was written by H. Xu with the help of B. Zhang.

ACRONYMS

ABWR	–	advanced boiling water reactors
AC	–	alternating current
AMP	–	accident management plans
AOO	–	anticipated operational occurrence
BDBA	–	beyond design basis accident
BDBEE	–	beyond-design-basis external event
CAE	–	emergency support center (in Spanish)
CAGE	–	alternative emergency management centre
CCF	–	common cause failure
CE	–	cliff edge
CEE	–	cliff-edge effect
DBA	–	design basis accident
DEC	–	design extension condition
DID	–	defense-in-depth
EDMG	–	extensive damage mitigation guideline
ELAP	–	extended loss of alternating current (AC) Power

EMEG – emergency mitigating equipment guideline
ENSREG – european nuclear safety regulators group
EOP – emergency operating procedure
EROS – emergency response data system
FLEX – diverse and flexible coping strategy
FSG – FLEX support guideline
HRA – human relinbility assessment
HSC – hardened safety core
IAEA – International Atomic Energy Agency
ITC – complementary technical instructions (in Spanish)
LOLA – loss of large area
LUHS – loss of ultimate heat sink
MACST – multi-barrier accident coping strategy
NEI – U.S. Nuclear energy institute
NO- – normal operation
NPP – nuclear power plant
NRC – nuclear regulatory commission
NTTF – near-term task force
PSA – probabilistic safety analysis
RCS – rector core cooling system
SA – severe accident
SAFER – strategic alliance for FLEX emergency response
SAMG – severe accident management guideline
SBO – station blackout
SFP – spent fuel pool
SSC – structure, systems and components

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ПРЕГЛЕД КОНЦЕПТА ОДБРАНЕ ПО ДУБИНИ И FLEX СТРАТЕГИЈА У РАЗЛИЧИТИМ ЗЕМЉАМА НАКОН НЕСРЕЋЕ У ФУКУШИМИ

Да би побољшао одбрану по дубини нуклеарне сигурности након несреће у Фукушими, Амерички институт за нуклеарну енергију изнео је концепт разноврсних и прилагодљивих стратегија деловања и одговарајуће FLEX смернице подршке за посебне сценарије продуженог губитка наизменичне струје и крајњег губитка снаге хладиоца узроковане спољашњим догађајем изван пројектних основа. Након тога, идеја FLEX стратегије широко је прихваћена и распростањена. Увођење концепта FLEX стратеије у одбрану по дубини било је највеће побољшање нуклеарне сигурности у последњој деценији. У раду је детаљно размотрен концепт традиционалне одбране по дубини и његове слабости које су довеле до нуклеарне несреће у Фукушими, што је изазвало пораст мотивације за развој FLEX стратегије. Приказан је преглед напретка истраживања FLEX стратегије у различитим земљама у последњих десет година. На основу литературе и наведеног прегледа представљене су неке препорукуе за будући рад.

Кључне речи: FLEX сшрашегија, одбрана по дубини, спољашњи догађај изван пројекшних основа, продужени губишак снаге наизменичне сшрује, крајњи губишак снаге хладиоца, нуклеарни акциденш у Фукушими