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Risk Reduction by Means of FLEX Strategies in Pressurized Water Reactors

Risk Reduction by Means of FLEX Strategies in Pressurized Water Reactors

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ABSTRACT

One of the key lessons learned from the Fukushima Dai-ichi accident was the importance of the challenge presented by the loss of safety-related systems after a Beyond Design-Basis External Event (BDBEE). In particular, Extended Loss of AC Power (ELAP) or Loss of Ultimate Heat Sink (LUHS) can severely compromise key safety functions associated with core cooling and containment, ultimately leading to reactor core damage. Because of that the so-called *Diverse and Flexible Coping Strategies* (FLEX) were designed.

These aforementioned FLEX strategies are also useful to avoid core damage in sequences due to internal events. Therefore, these FLEX strategies should be incorporated in the *Level 1 Probabilistic Safety Assessment* (L1PSA) to analyse their impact on core damage frequency (CDF). This work quantifies the impact of FLEX strategies by using a generic model (3 loops, PWR-WEC) developed by the UPM in collaboration with the Spanish Nuclear Regulatory Body (CSN). As a result, a decrease of the CDF at power for internal events is observed and, therefore, indicates that these FLEX strategies have a positive impact on the plant safety not only for BDBEE but also for other accidental conditions.

Acronyms

AFW Auxiliary Feedwater	LUHS Loss of Ultimate Heat Sink
BDBEE Beyond-Design-Basis External Event	NEI U.S. Nuclear Energy Institute
CDF Core Damage Frequency	NPP Nuclear Power Plant
EDG Emergency Diesel Generator	NRC Nuclear Regulatory Commission
EDMG Extensive Damage Mitigation Guideline	PSA Probabilistic Safety Assessment
ELAP Extended Loss of Alternating current (AC) Power	PWR Pressurized Water Reactor
FLEX Diverse and Flexible Coping Strategy	RCS Reactor Cooling System
FSG FLEX Support Guideline	SAMG Severe Accident Management Guideline
HRA Human Reliability Analysis	SBO Station Blackout
LOCA Loss-Of-Coolant Accident	SG Steam Generator

1 INTRODUCTION

Following the Fukushima Dai-ichi accident in 2011, the efforts of the nuclear industry and regulatory bodies at the international level have focused on increasing the defense in depth of nuclear power plants. The culmination of the joint work of different agencies, such as WENRA or NRC and the nuclear industry, has resulted in the creation of "FLEX Strategies" to increase plant capability in the face of BDBEE with the objective of avoiding significant reactor fuel degradation and ensuring the integrity of the fuel pool and containment. FLEX strategies must be able to counteract ELAP and LUHS conditions at the same time through alternative human actions and the use of portable equipment stored inside or outside the facility.

The FLEX strategies can be utilized also to prevent core damage caused by internal events sequences. As a result, incorporating these FLEX strategies into L1PSA allows for analysing their influence on the CDF. Related with this issue NEI 16-06 "Crediting Mitigating Strategies in Risk-Informed Decision Making" (NEI, 2016b) provides an approach in crediting the use of portable equipment associated with various plant mitigating strategies to restore or maintain various safety functions during beyond design basis conditions and the loss of permanently installed plant equipment. Also, this guidance describes examples on the use of FLEX-specific portable equipment and strategies.

Regarding to the implementation of the FLEX equipment on PSA found in the literature, the following can be highlighted: Fujioka et al. (2017) conducted a study to analyze the effectiveness of SFP FLEX strategies in a LUHS scenario caused by a tsunami; Jabbari et al. (Jabbari et al., 2020) analyze the introduction of a portable air-cooled diesel generator for ELAP scenario mitigation in VVER-1000 NPP and verified its effectiveness; Gjorgiev et al. (Gjorgiev et al., 2017) analyze the introduction of independent water storage systems to enhance the safety of a typical PWR in an SBO scenario; Hakobyan et al. (Hakobyan & Nierode, 2017) analyze the implementation FLEX strategies in Surry NPP PSA; Zhang et al. (Zhang & Ma, 2020) study the impact of FLEX strategies in a dual-unit site experiencing LOOP; Kim et al. (J.-S. Kim et al., 2021) include portable equipment in the PSA model for WH600, WH900, OPR1000 and APR1400 reactors in Korea obtaining the CDF reduction; Tabadar et al. analyze the effectiveness of portable equipment in LUHS accidents for VVER-1000. (Tabadar et al., 2019b, 2019a). Other researchers, such as Kim & Kim (J.-S. Kim & Kim, 2021); Lim (Lim, 2018); Islam et al. (Islam & Lim, 2017); Webster (Webster, 2017) and París et al. (París et al., 2019) have also employed the PSA method to study FLEX strategies for different scenarios and nuclear power plants.

Also, Idaho National Laboratory (INL) has developed extensive work regarding FLEX strategies, including incorporating them into PWR models: Ma et al. (Ma et al., 2019) crediting FLEX in PSA, incorporating them to the generic loss of offsite power (LOOP)/SBO; and into BWRs (Ma et al., 2020); a FLEX HRA approach on how to perform human reliability analysis (HRA) for FLEX applications (Ma et al., 2020) and later extending the EMRALD tool to FLEX dynamic HRA (J. Park et al., 2021, 2022); and reviewed the development and use of weakly informed a priori distributions to obtain industry-wide probability and failure rate distributions (Gentillon et al., 2020). Finally, the NRC also crediting FLEX in their accident sequence precursor (ASP) analysis (NRC, 2012, 2020c) and have already incorporated the FLEX Strategies in their all 71 Standardized Plant Analysis Risk (SPAR) models (Ng, 2020).

While FLEX strategies are initially proposed to cope with an ELAP and LUHS following a BDBEE, this work is focused on modeling and analyzing the total impact of FLEX strategies on the L1PSA, regardless of the initiating event, at nominal power.

In addition to this Introduction Section, the present paper is organized as follows: Section 2 describes the main premises, scope, and data sources of the L1PSA model. Section 3 resumes some Post-Fukushima improvements, introduces the most common FLEX strategies used and how they are linked to the other mitigation strategies. Section 4 outline the FLEX modeling with a description of representative examples of Event Tress (ET), Fault Tress (FT), Human Reliability Analysis (HRA) and Data for FLEX equipment. Section 5 summarizes the results obtained with the model and how the inclusion of FLEX strategies affects the risk. Section 6 presents a sensitive analysis to understand the impact of every FLEX strategy by separate. Finally, the conclusions drawn from this research are set out in Section 7.

2 GENERIC PWR LEVEL 1 PSA MODEL

The regulatory activity requires the oversight of licensee performance to be made from an independent position. This position is better served when the regulatory body develops its own methodologies and tools. In particular, in the matter of probabilistic risk analysis, even if the licensees' analyses are subject to peer-review and/or are reviewed by the regulatory body, it is very difficult to manage the large number of hypotheses and assumptions behind the model. Thus, the development of a PSA model for regulatory use improves the knowledge of the nuclear power plants (NPPs) risks and can be seen as an enhancement of the regulatory practice.

On this regard, the Spanish Nuclear Regulatory Body (CSN), in collaboration with the Universidad Politécnica de Madrid (UPM), have been assembling its own generic Standardized Plant Analysis Risk (SPAR) model (SPAR-CSN) for 3-loop PWR-WEC designs. The current purpose of the project considers the elaboration of a standardized PSA model independent from the industry, providing a high-level view of risk in the evaluation of findings in Spanish NPPs, and intended to be comparable in scope to United States Nuclear Regulatory Commission (NRC) SPAR models (NRC, 2010b, 2010a; Watanabe et al., 2018) . To this end, the conclusions drawn from the comparison of the existing industry models are used to establish a common set of assumptions and standard modeling techniques to be used in CSN models (Meléndez et al., 2016). This type of model improves the understanding of the risks of nuclear power plants and is considered an improvement of regulatory practice. The SPAR-CSN model aims to:

- Understand the main risk factors of the different nuclear power plants.
- Help define the areas of inspection and supervision tasks by using measures of the importance of the systems and components.
- Evaluate inspection performed within the Spanish regulatory system, SISC.
- Perform precursor analyses of events occurring at NPPs in Spain.
- Evaluate and identify the differences between the PSA models of the Spanish NPPs, to help in the assessment and verification of those models.

The configuration of the different systems and components as well as the assumptions taken for the modeling is a composite chosen to be representative of most of the plants. The model has 14 main ETs, Table 1:

Table 1: List of ETs of the SPAR-CSN model

ID	Initiating event	ID	Initiating Event
LBLOCA	LOCA (> 6 in.)	**MSLB-US**	Main Steam Line Break Upstream of MSIV
MBLOCA	LOCA (2 in. to 6 in.)	**MSLB-DS**	Main Steam Line Break Downstream of MSIV
SBLOCA	LOCA (3/8 in. to 2 in.)	**SGTR**	Steam Generator Tube Rupture
GT	General Transient	**LCWA**	Loss of a Component Cooling Water System (CCWS) Train

ATWS	Anticipated Transient Without Scram	**LNSW**	Loss of Non-essential Service Water System
LC	Loss of Condenser	**LOOP/SBO**	Loss of Offsite Power/ Station Blackout
LDC-A	Loss of Emergency DC-A Bus	**LDC-B**	Loss of emergency DC-B bus

To define the different sequences of each ET, a mission time of 24 hours and two different consequences, safe stable state (S) or core damage (CD), are considered. A safe stable state is defined as follows in NUREG-2122 (NRC, 2013): "condition of the reactor in which the necessary safety functions are achieved".

Table 2 summarizes the scope of the SPAR-CSN model regarding the FTs task. In its final version, 18 safety systems are included, with 539 FT pages and 1381 basic events.

Table 2: List of system FTs of the SPAR-CSN model

ID	System	ID	System
AC	Emergency AC distribution system	**IA**	Instrumentation Air System
AF	Auxiliary Feedwater System	**LH**	Low Pressure Injection System
AI	Accumulators Injection System	**MS**	Main Steam System
CW	Component Cooling Water System	**NC**	Non-essential Component Cooling Water
DC	Emergency DC distribution system	**NS**	Non-essential Service Water System
DG-A/B	Emergency Diesel Generators	**PR**	RCS Pressure Relief System
DG-SBO	SBO Diesel Generator	**RP**	Reactor Protection System
ES/SQ	ESFAS/Sequencer	**SC**	RCS Seal Injection System
HH	High Pressure Injection System	**SW**	Essential Service Water System

All failures considered in the FTs occur during mission time. A single unavailability basic event due to maintenance or testing is associated to each train of each safety system. A high-level representation of the failure of the automatic startup signals is modeled, which includes the potential loss of the required AC/DC power supply and a single undeveloped basic event representing the signal generation failure. The connection between ETs headers and FTs is made through the corresponding function trees.

Regarding human reliability, the model uses the SPAR-H methodology (NRC, 2005) to quantify the probability of the different type-3 human errors, following the methodology of the SPAR-NRC models, it is worth mentioning that the NRC is currently modifying the methodology to IDHEAS. The generic SPAR-CSN model includes a total of 38 human actions. The choice of the human actions was based on the Emergency Operating Procedures (EOPs) of the Spanish NPPs. The human reliability parameters have been obtained from actual data from Spanish NPPs.

To obtain the reliability parameter data for the different basic events related to system unavailability, equipment failures, and initiating events, public data have been used as a source; NUREG/CR-6928 (NRC, 2007) and NUREG/CR-5497 (Marshall et al., 1998).

The only Post-Fukushima improvement included in the initial PSA model is the Passive Thermal Shutdown Seals (SDS). These are ring-shaped devices placed on the Reactor Coolant Pumps (RCPs) designed to prevent leakage in case of loss of seal injection. The SDS have specific part which degrades and disappears at high-temperature allowing the movement of two annular pieces in contact that, thanks to the direction of water flow, are positioned in such a way that they completely seal the coolant leakage path through the pump. These passive seals act in situations such as loss of external AC current, with consequent tripping of the pumps and no injection of coolant to seals, but cooling of the three steam generators is still required to be maintained. The SDS shows a positive impact and a significant increase the margin to core uncover in several circumstances and reduce the CDF (Mena-Rosell et al., 2018).

Beyond the use and validation of this model, the present paper introduces an extension of the scope of the initially foreseen applications to the goal of evaluate the impact of the implementation of FLEX strategies in L1PSA.

3 FLEX STRATEGIES AND PORTABLE EQUIPMENT

Following the Fukushima Dai-ichi accident, the culmination of the joint work of different agencies to increase the defense in depth, resulted in the creation of NEI 12-06, Diverse and Flexible Coping Strategies (FLEX) Implementation Guide (NEI, 2012), where the term "FLEX Strategies" is defined for the first time. This document defines FLEX as strategies to increase plant capability against of Design-Basis External Event (BDBEE) with the objective of avoiding significant reactor fuel degradation and ensuring the integrity of the fuel pool and containment. FLEX strategies must be able to counteract ELAP and LUHS conditions at the same time, as a consequence of a BDBEE, through alternative human actions and the use of portable equipment, stored inside or outside the facility. This guide proposes an implementation of FLEX strategies divided into three phases:

- Phase 1: Utilization of "Pre-staged" fixed plant equipment, this equipment belongs to the safeguards systems or to other systems and can be realigned to cope with the accident situation (e.g. Diesel Driven-Pump of the Fire Protection System, DDP-FPS; hydrostatic test pump).
- Phase 2: Transition from using fixed plant equipment to portable equipment or FLEX equipment located on site to maintain safety functions for a longer period.
- Phase 3: Obtaining additional mitigation capacity by transporting and deploying redundant FLEX equipment from a site outside the nuclear plant. This last stage allows safety functions, such as power supply or coolant injection, to be extended over a virtually unlimited period.

The portable equipment most commonly incorporated in NPPs to implement FLEX strategies Phase 2 includes, Table 3 and Table 4:

1. FLEX-DG: Portable diesel generator for alternate AC supply.
2. FLEX-SGP: Low-pressure portable pump for alternative injection to SGs.
3. FLEX-MUP: High-pressure portable pump for alternative make-up and boration into the RCS.
4. FLEX-HCP: Very low pressure, high-capacity portable pump for coolant drive from the ultimate heat sink.
5. FLEX-SUP: Very low-pressure submersible pump for pumping coolant from the ultimate heat sink.

It is important to note that the mass-flow rate of some pumps vary greatly from plant to plant and, therefore, may not have the same effectiveness in FLEX strategies. On the other hand, it should be noted that the characteristics of the DDP-FPS are approximately 200 kg/s and 10 bar (FLEX strategies Phase 1).

Other devices are also mentioned: small portable containers of fuel; Gas Turbine-driven generator for alternative AC supply (CTG-AC) or DC supply (CTG-DC); hands free battery powered portable lights; and portable instrumentation. In addition, the U.S. nuclear industry applies the N+1 approach, this implies that for every unit present on the site, an additional equipment, connection point, or equivalent safeguard measures must be installed to ensure defense-in-depth (NEI, 2012). The NEI-12-06 approach is not applied worldwide, e.g. South

Korea applies the RObust Coping Strategy (iROCS) (J. Kim et al., 2016) and Multi-barrier Accident Coping Strategy (MACST) (J.-K. Park et al., 2018); Canada applies the Emergency Mitigating Equipment Guidelines (EMEGs) (CNSC, 2015); and France applies Hardened Safety Core (HSC) (Xu & Zhang, 2021).

Table 3: FLEX equipment in PWR-WEC US NPP.

NPP	FLEX-DG P[kW]/V[V]	FLEX-SGP Q[kg/s]/P[Bar]	FLEX-MUP Q[kg/s]/P[Bar]	FLEX-HCP Q[kg/s]/P[Bar]	FLEX-SUP Q[kg/s]/P[Bar]
(Braidwood Station, 2017)	350/480	30/28	2/103	91/10	
(Byron Station, 2013)	500/480	18/21	2/103	66/15	
(Donald C. Cook, 2015)	N/A/600 & N/A/480	36/28	1.6/107	20/21	
(Joseph M. Farley, 2013)	N/A/600 & N/A/480	18/21	1.2/36	6/3	
(McGuire, 2016)	500/600	18/28	N/A	91/N/A	6/N/A
(North Anna, 2016)	40/120-240 & 350/480	N/A	3/N/A	N/A	
(Point Beach, 2015b)	404/480	20/28	4/N/A & 1/138		
(H. B. Robinson, 2015)	N/A/480	18/69	4/138	36/5	
(Salem Station, 2014)	N/A/480	N/A	N/A	42/N/A	N/A
(Seabrook Station, 2016)	405/480 & 30/N/A	20/28	1/103		20/3
(Sequoyah, 2016)	3000/6900 & 225/480		2/41	302/10	302/2
(Shearon Harris, 2016)	830/480	20/25	2/110	181/10	
(South Texas, 2016)	1000/480	18/35	4/48	60/10	
(Summer, 2016)	80/480 & 300/480	30/0.4 & 30/35	4/138	48/N/A	N/A
(Surry Power Station, 2016)	350/480 & 40/120	18/31	3/138	72/10	
(Vogtle, 2016)	350/480	21/28	1/36	N/A	30/7

Table 4: FLEX equipment in PWR-WEC Spain NPP.

NPP	REF	FLEX-DG P[kW]/V[V]	FLEX-SGP Q[kg/s] /P[Bar]	FLEX-MUP Q[kg/s] /P[Bar]	FLEX-HCP Q[kg/s]/P[Bar]	FLEX-SUP Q[kg/s]/P[Bar]
ALMARAZ	(CSN, 2015)	N/A	29/15	12/23		
ASCÓ	(CSN, 2013a)	550/N/A	N/A	19/28		N/A
VANDELLOS	(CSN, 2014)	550/N/A	19/20	4/20	246/12	N/A

3.1 EXTENSIVE DAMAGE MITIGATION GUIDELINES AND FLEX SUPPORT GUIDELINES IN USA AND SPAIN

In response to the September 11, 2001, terrorist attacks, the Nuclear Regulatory Commission (NRC) issued Order EA-02-026, known as the Interim Safeguards and Security Compensatory Measures (ICM) Order, in February 2002. This order imposed new requirements on licensees, specifically in Section B.5.b, which mandated the implementation of mitigation strategies using readily available resources to ensure the maintenance or restoration of core cooling, containment, and Spent Fuel Pool (SFP) cooling capabilities (Caro, 2012). These strategies were intended to address the potential Loss of Large Areas (LOLA) of the facility due to various types of large fires and explosions, including those caused by aircraft impacts beyond the Design Basis. As a result, U.S. Nuclear Energy Institute (NEI) introduced in 2005 the Extensive Damage Mitigation Guidelines (EDMGs) (Xu et al., 2021). In December 2006, the NRC endorsed Revision 2 of NEI 06-12 (NEI, 2009), as an acceptable method for developing the mitigation strategies required in Section B.5.b.1 of the ICM Order. Section 3.3 of NEI 06-12 guideline establishes enhanced site response strategies for PWRs:

- Makeup to RWST
- Manually Depressurize SGs to Reduce Inventory Loss
- Manual Operation of Turbine-Driven (or diesel-driven) Pump of AFW (TDP-AFW)
- Manually Depressurize SGs and Use Portable Pump
- Makeup to Condensate Storage Tank (CST)/AFW Storage Tank
- Containment Flooding with Portable Pump
- Portable Sprays

Later, after the Fukushima accident, in 2012, NEI released the first version of the document NEI 12-06(NEI, 2012). To supplement the guidance in NEI 12-06, in 2012, the PWROG in collaboration with Westinghouse started the project titled "Emergency Response to Extended Station Blackout Events," (PA-PSC-0965). The project objectives included creating universal FLEX Support Guidelines (FSGs), recognizing links to existing EOPs, identifying crucial plant instruments to be utilized during battery load-shedding approaches, and establishing a general framework for the timing and selection of portable equipment and techniques to respond to an ELAP (PWROG, 2012). Westinghouse document WCAP-17601 presented the findings of the baseline thermal-hydraulic analyses conducted to examine the response of the primary system and the cooling down of the plant during an ELAP (Stringfellow, 2017). The analyses aimed to provide a better understanding of the system's behavior and trends in such events. Then, in 2014, the report WCAP-17792-P, addressed issues identified in WCAP-17601 (Stringfellow, 2017).

The FSGs should include clear instructions for operators on when and how to use the FLEX equipment. These guidelines should be tailored to the specific needs of each plant, considering the FLEX strategies and modifications adopted for that particular plant. The procedures must be implemented in a plant-specific manner to ensure their effectiveness. The list of standardized FSGs is as follows (Point Beach, 2015a; Xu & Zhang, 2021):

- FSG-0: FLEX Information and Reference Guide
- FSG-1: Long Term RCS Inventory Control
- FSG-2: Alternate Auxiliary Feedwater (AFW) Suction Source
- FSG-3: Alternative Low-pressure Feedwater
- FSG-4: ELAP Power Management
- FSG-5: Initial Assessment and FLEX Equipment Staging
- FSG-6: Alternate Condensate Storage Tank Makeup
- FSG-7: Loss of Vital Instrument or Control Power
- FSG-8: Alternate RCS Boration
- FSG-9: Low Decay Heat Temperature Control
- FSG-10: Passive RCS Injection Isolation
- FSG-11: Alternate SFP Makeup Equipment Deployment

- FSG-12: Alternate Containment Cooling (Shutdown Only)
- FSG-13: Transition from FLEX Equipment
- FSG-14: Shutdown RCS Makeup

In Spain the process followed was different from that in the USA. In 2011, the CSN issued Complementary Technical Instructions ITC-1 (CSN, 2011) and ITC-2 (CSN, 2011b). These concentrate the main guidelines of the new extensive damage mitigation strategies, introducing portable equipment, alternative water sources and alternative power supplies. The ITC-2 was related to the NEI 06-12 guide and focused on the possibility of LOLA. As a result of the analyses carried out by the plants, imposed by these technical instructions, the new EDMGs were implemented during 2012-2013 (Hernández et al., 2015; Queral & Alonso-Escos, 2023). The way these strategies are implemented depends on the plant itself and, therefore, varies from plant to plant. A generic EDMGs list corresponding to the Spanish PWR NPPs is (CSN, 2013; Gil Rodríguez et al., 2016; Queral & Alonso-Escos, 2023)

- EDMG-1: Instrumentation recovery
- EDMG-1.1: Manual operation of the TDP-AFW
- EDMG-1.2: Decrease pressure of SGs and flow control of AFW
- EDMG-1.3: Decrease pressure of SGs and flow control with portable HP pump
- EDMG-1.4: Decrease pressure of SGs and flow control with portable LP pump
- EDMG-1.5: Decrease pressure of SGs and flow control with DDP-FPS
- EDMG-1.6: Supply to the water tank to support the AFW system
- EDMG-2.1: Water supply to the RCS by means of hydrostatic test pump
- EDMG-2.2: Water supply to the RCS by portable HP pump through RHR
- EDMG-2.3: Water supply to RWST
- EDMG-3.1: Water supply to the spent fuel pool (SFP)
- EDMG-3.2: Direct spraying of the SFP
- EDMG-3.3: Minimizing leakage in the SFP
- EDMG-4.1: Flooding of containment through containment spray lines
- EDMG-4.2: Spraying of containment leaks
- EDMG-4.3: Filling of the reactor cavity
- EDMG-4.4: Pressure control of the containment building
- EDMG-5.1: Installation of portable diesel generator and connection of loads
- EDMG-5.2: Portable LP pump installation and start-up
- EDMG-5.3: Portable HP pump installation and start-up
- EDMG-5.4: Refueling of portable equipment with tanker truck
- EDMG-5.5: Portable communication module installation and start-up
- EDMG-5.6: Portable meteorological station installation and start-up

In recent years, due to the development of the FSGs, implemented and updated in Spain from 2017 to 2022 (Queral & Alonso-Escos, 2023), the structure of the procedures and guidelines has been changed in Spanish NPPs. The present relationship between guidelines and procedures in Spain depends on the nature of the initiating event, Figure 1:

- A first possible scenario is the corresponding one to level 1 PSA where an incident due to an internal event, the management is done through the EOPs (at power) or the AOPs (at shutdown). In the case that the strategies considered in the EOPs/AOPs are not effective, the FSGs that are referenced in these EOPs/AOPs will be applied, Table 5, and in the event that these are not effective either, the strategies of the EDMGs can also be used at the discretion of the Senior Reactor Operator (SRO). If despite the application of all the above strategies, the incident cannot be controlled, a severe accident situation will be reached and it will be necessary to apply the Severe Accident Mitigation Guidelines (SAMGs), this situation is part of the level 2 PSA.

- A second possible scenario is a BDBEE that produces catastrophic damage, in which case the Emergency Management Guideline (EMG) must be applied; these are alternative methods in events that could result in severe damage as the total loss of energy and/or inability to operate from the MCR and the remote shutdown panel, or catastrophic failure of vital structures. In these situations, the anticipated command and control of the emergency might be not available. The EMG are directly related to the EDMGs.

As a final remark, the relationship of EOPs, FSGs, EDMGs and SAMGs in Spanish NPPs is similar, although with certain differences, to the structure proposed by the NEI 14-01 guide (NEI, 2016a) adopted by the US NPPs.

In order to compare EDMGs and FSGs, it can be mentioned that EDMG motivation and objectives were implemented to mitigate LOLA and maintain fuel cooling and containment capabilities. FSGs were implemented to mitigate BDBEE and also to maintain fuel cooling and containment capabilities. Regarding the strategic features, EDMG establish an initial command and control in case the normal command and control is disrupted, and use temporary and portable equipment in a local and manual mode. In contrast, FSGs use a three-phase FLEX approach (J. Kim et al., 2016).

According to the scope of the generic PWR L1PSA model used (see section 2), the FSGs that have been considered are FSG-1, FSG-3, FSG-4, FSG-5, FSG-7 and FSG-8. Also, are considered EDMG-1.1, EDMG-1.4, EDMG-1.5, EDMG-2.2, EDMG-2.3, EDMG-5.1, EDMG-5.2 and EDMG-5.3.

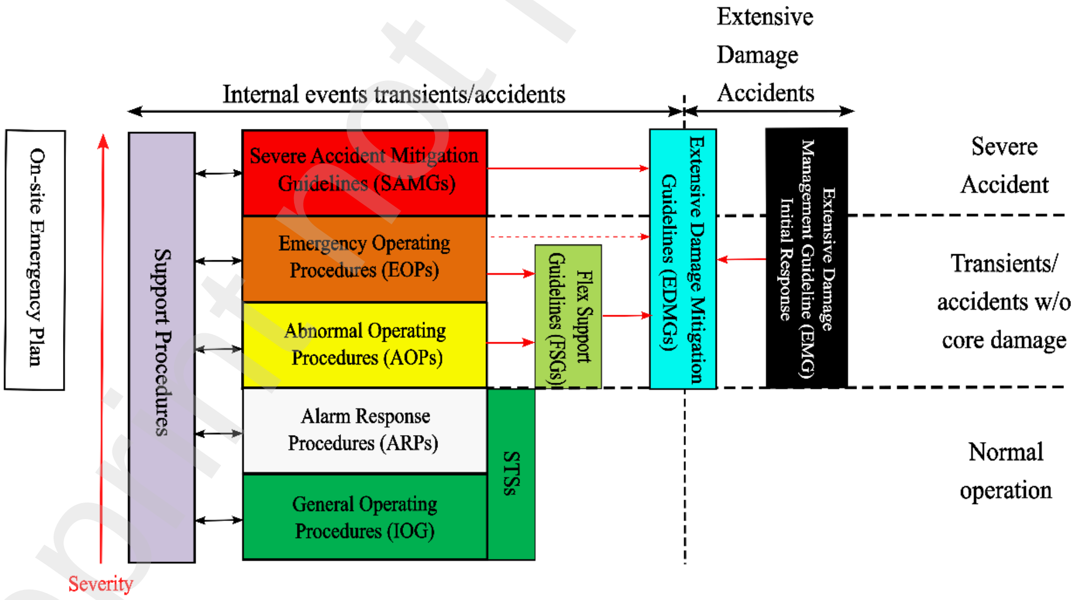

Figure 1: Procedures and guidelines relationships in Spain (Queral & Alonso-Escos, 2023).

Table 5: Entry to FSG procedures (Queral & Alonso-Escos, 2023)

FSG	From EOP	From AOP
FSG-1	ECA-0.0; FR-C.1; FR-C.2	
FSG-2	ECA-0.0	ARG-4
FSG-3	ECA-0.0; FR-H.1; FR-C.1	ARG-4
FSG-4	ECA-0.0	ARG-4
FSG-5	ECA-0.0	ARG-4
FSG-6	ECA-0.0	ARG-4
FSG-7	ECA-0.0	ARG-4
FSG-8	ECA-0.0; FR-S.1	
FSG-9	ECA-0.0	ARG-4
FSG-10	ECA-0.0	ARG-4
FSG-11		ARG-4
FSG-12	ECA-0.0	ARG-4
FSG-13	ECA-0.0	ARG-4
FSG-14		ARG-4

4 FLEX STRATEGIES MODELLING

The incorporation of FLEX strategies into the PSA model requires the modification of the event trees, development of the fault trees corresponding to each new FLEX system and FLEX strategies; analysis of new human actions; and analysis of databases for FLEX equipment. The equipment considered within the modeling is: 1 DDP-FPS; 1 FLEX-SGP; 1 FLEX-MUP; 1 FLEX-DG; 1 FLEX-HCP. The inclusion of FLEX strategies in the L1PSA has been done considering a series of specific actions and equipment. These FLEX Actions (FA) are:

- FA-1: Alternative low-pressure feedwater to the SGs by FLEX-SGP.
- FA-2: Alternative low-pressure feedwater to the SGs by DDP-FPS.
- FA-3: Manual operation of TDP-AFW after DC loss.
- FA-4: Long Term RCS Inventory Control by FLEX-MUP.
- FA-5: Alternative RCS boration by FLEX-MUP.
- FA-6: Alternative RWST inventory control by DDP-FPS.
- FA-7: Alternative RWST inventory control by FLEX-HCP.
- FA-8: Supply of AC power by FLEX-DG.
- FA-9: DC load shedding to increase battery life.

It is important to note that each plant may have other FA depending on its own capabilities. These FA are applied according to the FSGs and EMDGs as shown in Table 6. The modelling of the FA is described in the following Sections: Section 4.1 describes the new ETs including the FLEX headers. The modeling of FT and the corresponding new function events is presented in Section 4.2. The data sources used in the model are described in Section 4.3. Finally, Section 4.4 explains the human reliability analysis (HRA) approach used.

Table 6: FLEX Actions and relationship with FSGs and EDMGs

FLEX Action	FSG	EDMG	Equipment
FA-1: Alternative low-pressure feedwater to the SGs by FLEX-SGP.	FSG-3	EDMG-1.4 EDMG-5.2	FLEX-SGP
FA-2: Alternative low-pressure feedwater to the SGs by DDP-FPS.	FSG-3	EDMG-1.5	DDP-FPS
FA-3: Manual operation of TDP-AFW after DC loss.	FSG-7	EDMG-1.1	TDP-AFW
FA-4: Long Term RCS Inventory Control by FLEX-MUP.	FSG-1	EDMG-2.2 EDMG-5.3	FLEX-MUP
FA-5: Alternative RCS boration.	FSG-8		FLEX-MUP
FA-6&7: Alternative RWST Inventory Control w/ Diesel-driven Pumps		EDMG-2.3	FLEX-HCP DDP-FPS
FA-8: Supply of AC power by FLEX-DG.	FSG-4	EDMG-5.1	FLEX-DG
FA-9: DC load shedding to increase battery life.	FSG-4		Batteries

4.1 EVENT TREES INCLUDING FLEX HEADERS

To include FLEX strategies in ET, it is necessary to identify which initiators and sequences can include these strategies. Then, the corresponding FLEX actions are introduced either within a pre-existing system, which implies modifying the header, or creating a new header if the FLEX action is not part of any previously defined system. In this process, thermal-hydraulic simulations are of great importance, as they give credibility to the FLEX actions in the model, especially in the quantification of the available times, given that the performance of many FLEX actions are not immediate and require certain time to be implemented.

The addition of the above-mentioned FLEX Actions, Table 6, configures the new ETs of the model; this include the following new (or modified) headers with their corresponding function events, boundary conditions and success criteria. The modified headers, new ones and their related FLEX actions are, see also Table 7:

- AF+FLEX: Residual heat removal through the secondary with diesel pumps FLEX-SGP or DDP-FPS or TDP-AFW (FA-1, FA-2).
- FLEX-MUP: Coolant injection into the RCS with the FLEX-MUP diesel pump (FA-4).
- FLEX-MUP-RWST: Alternate RCS boration with FLEX-MUP from RWST (FA-5).
- LB+FLEX: Power supply to loads (DC-B/C buses) from DG-SBO or FLEX-DG (FA-8).
- LBS: DC load shedding of non-essential loads from batteries (FA-9).
- RWST-FLEX: RWST inventory control with FLEX-HCP or DDP-FPS (FA-6, FA-7).
- TDP-MANUAL: Manual operation of the TDP-AFW (FA-3).

Although not considered a FLEX strategy as such, the recovery of at least one EDG has also been modeled together with the recovery of the external AC power, even if the probability of recovery in the short term is low and depends on the EDG failure type. The new AC recovery header is called R-EX+R-DG.

Figure 2 shows the new ET configuration for LOOP-SBO. In this new ET a new sequence can be observed: the injection of coolant into the RCS by means of the FLEX-MUP pump would produce a Feed & Bleed (F&B) type situation that would allow compensating the RCS inventory loss after the failure of the passive thermal seals. This pump may or may not be effective depending on the mass-flow rate it can provide. Figures 3, 4, 5 and 6 show the new ETs for GT, SBLOCA and SGTR initiators respectively. The ETs for LC, LDC-A and LDC-B are similar to GT ET, the MBLOCA ET is similar to SBLOCA one. For LBLOCA and LNSW no FLEX actions have been considered.

Table 7: FLEX headers included in each ET (M: Modified; N: New)

ET	FLEX Headers						
	AF+FLEX	FLEX-MUP	LB+FLEX	LBS	R-EX+ R-DG	TDP-MANUAL	RWST-FLEX
LBLOCA	-	-	-	-	-	-	-
MBLOCA	-	**N**	-	-	-	-	**N**
SBLOCA	**M**	**N**	-	-	-	-	**N**
GT	**M**	-	-	-	-	-	**N**
LC	**M**	-	-	-	-	-	**N**
MSLB-DS	**M**	-	-	-	-	-	**N**
MSLB-US	**M**	-	-	-	-	-	**N**
LCWA	**M**	-	-	-	-	-	-
SGTR	-	-	-	-	-	-	**N**
LNSW	-	-	-	-	-	-	-
LDC-A	**M**	-	-	-	-	-	**N**
LDC-B	**M**	-	-	-	-	-	**N**
LOOP	**M**	**N**	**M**	**N**	**M**	**N**	-

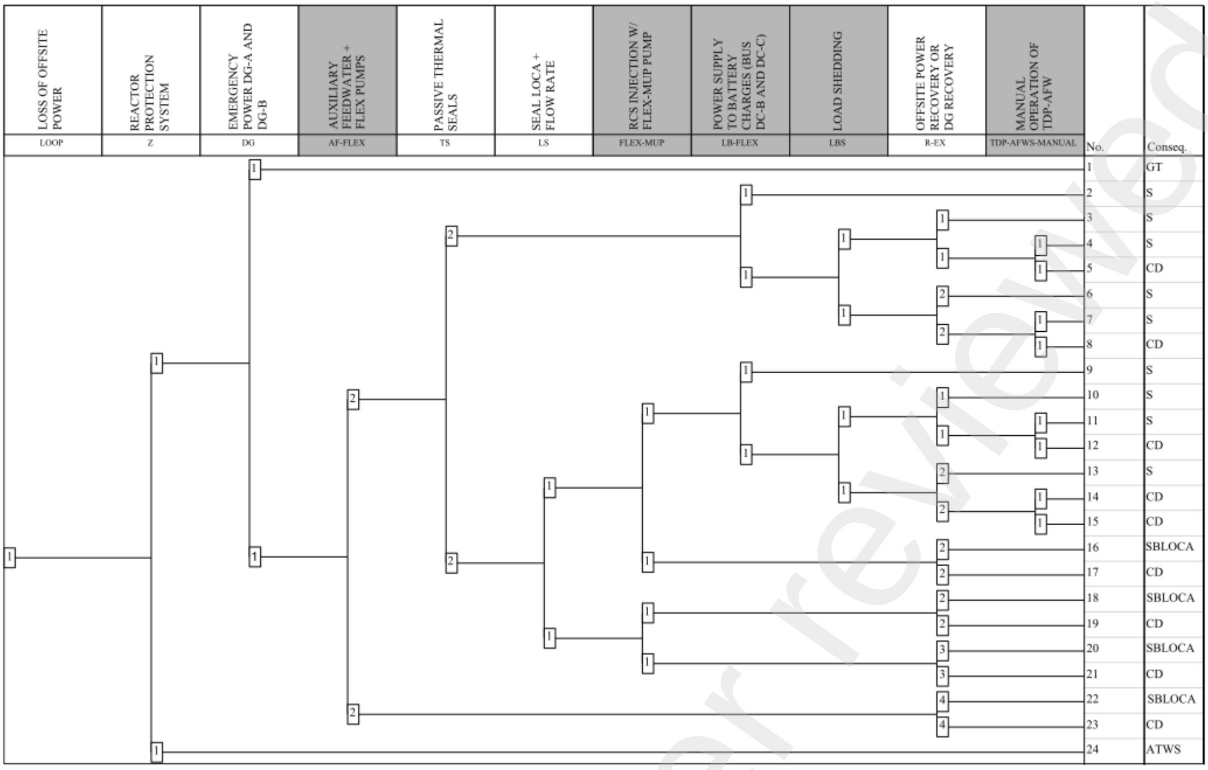

Figure 2: LOOP-SBO event tree with FLEX strategies.

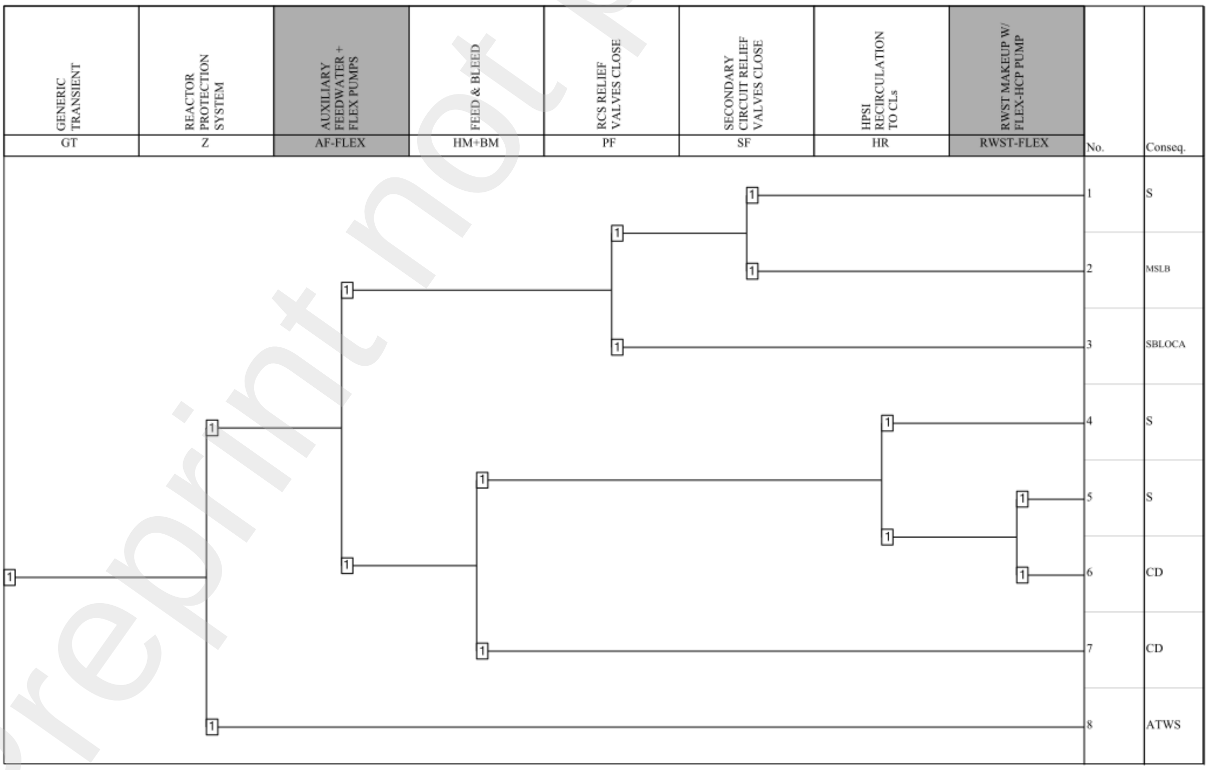

Figure 3: GT event tree with FLEX strategy.

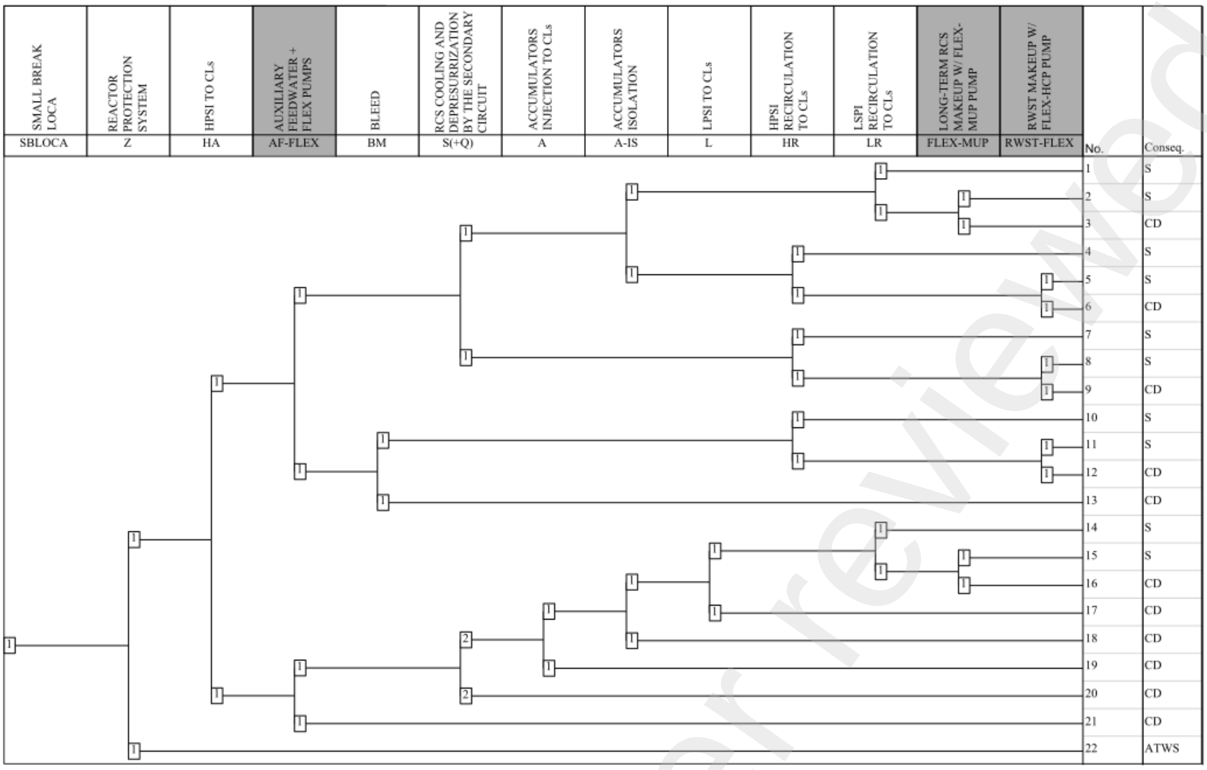

Figure 4: SBLOCA event tree with FLEX strategy.

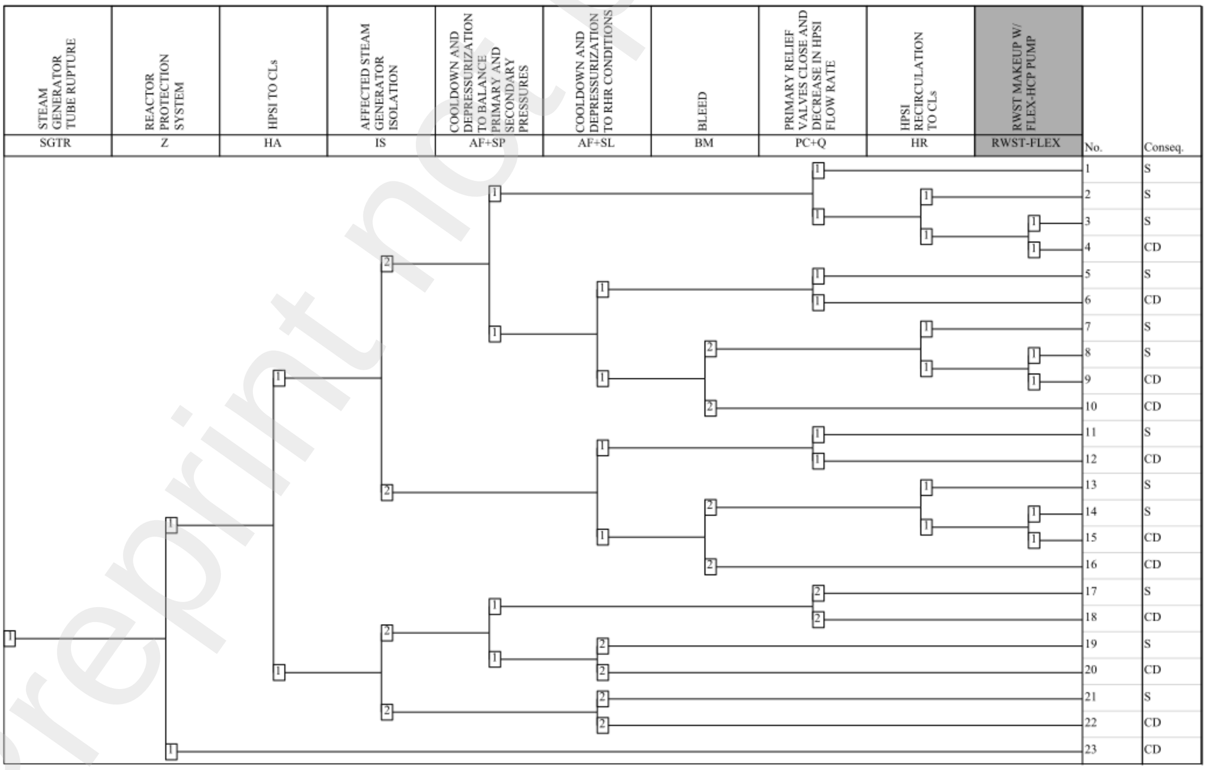

Figure 5: SGTR event tree with FLEX strategies.

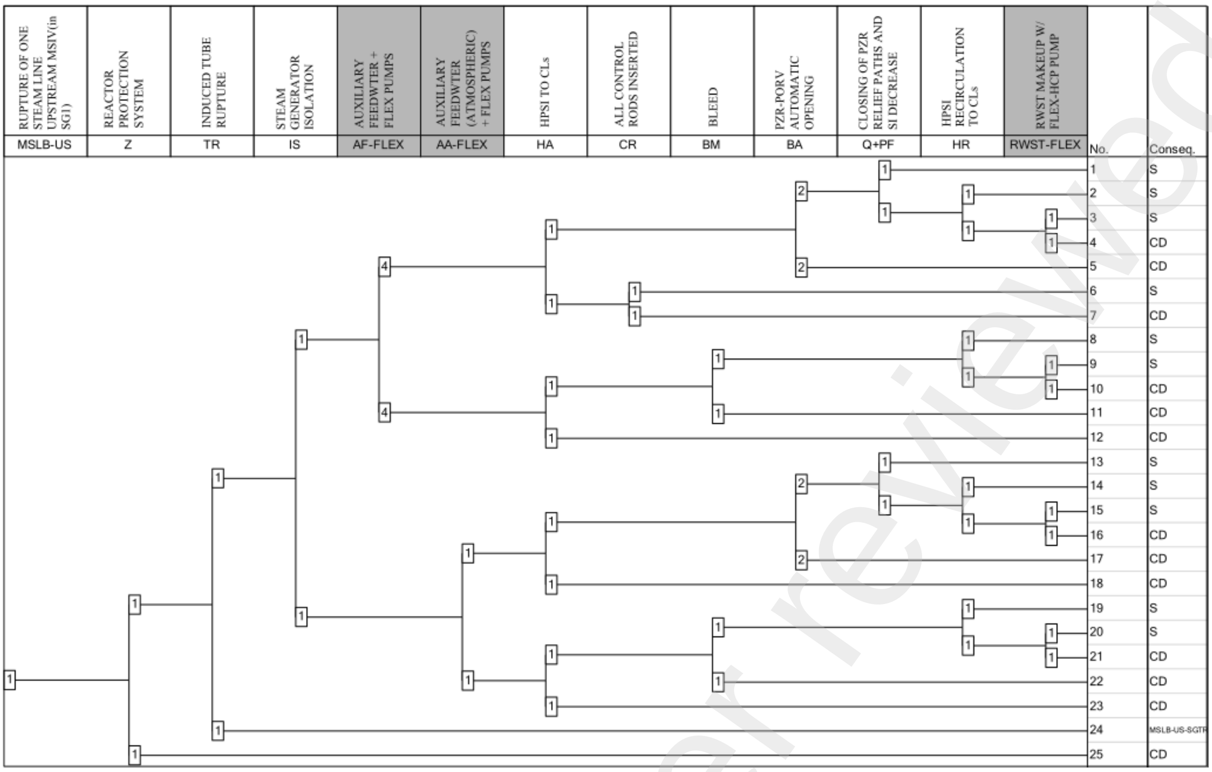

Figure 6: SLB event tree with FLEX strategies.

4.2 FAULT TREES (FT)

The modeling of the fault trees (FT) includes failures associated with portable equipment (fail to start, fail to run and unavailability due to maintenance or test) and human actions (Human Failure Event, HFE). The new FT model FLEX Strategies for AFWS (including FLEX-SGP FT and DDP-FPS FT), Figure 7, and the FT for other equipment (FLEX-MUP, FLEX-DG and FLEX-HCP), Figure 8. Also included are the new top event fault tree: Heat removal via the SG with FLEX; Emergency boration with FLEX; Supply of battery charges with FLEX-DG; RWST makeup with FLEX-HCP pump; Load shedding of non-essential loads from the batteries; Manual operation of the TDP –AFW; and RCS injection with FLEX-MUP pump.

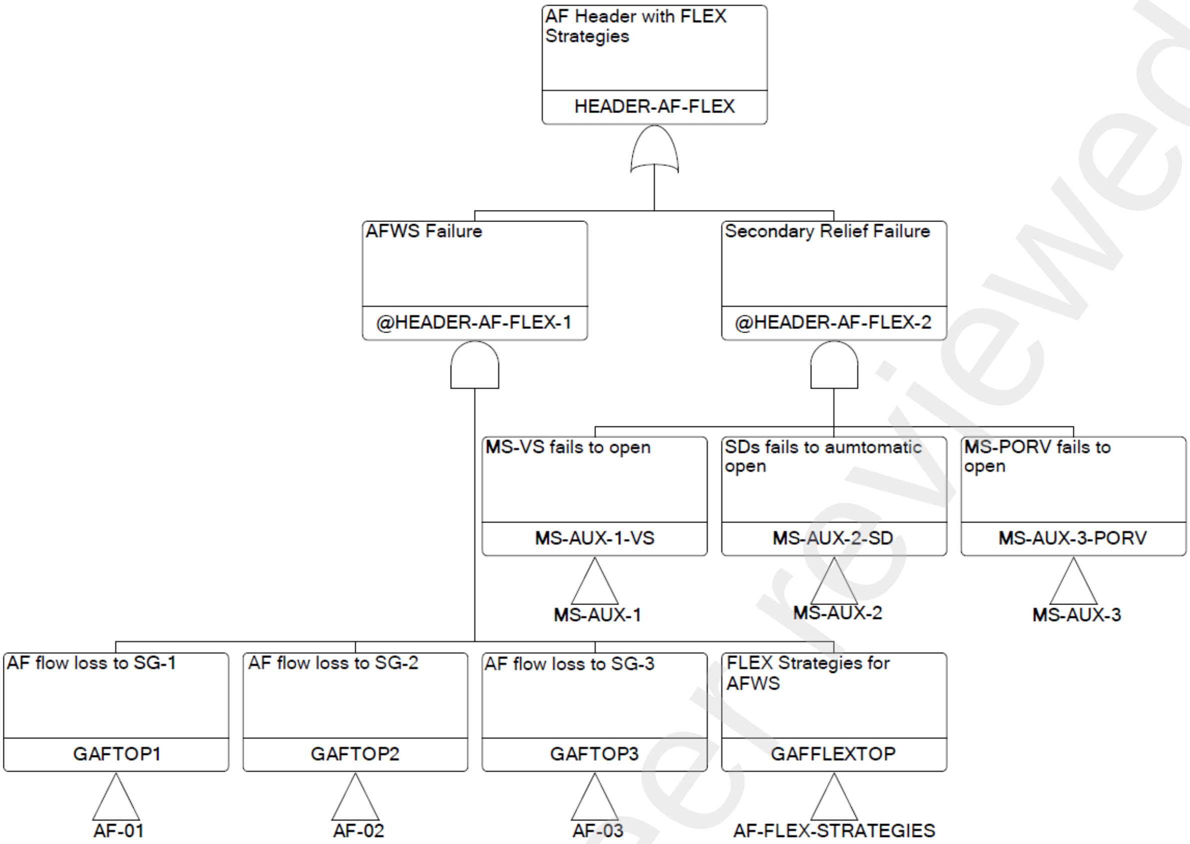

Figure 7: Top event fault tree corresponding to AF Header

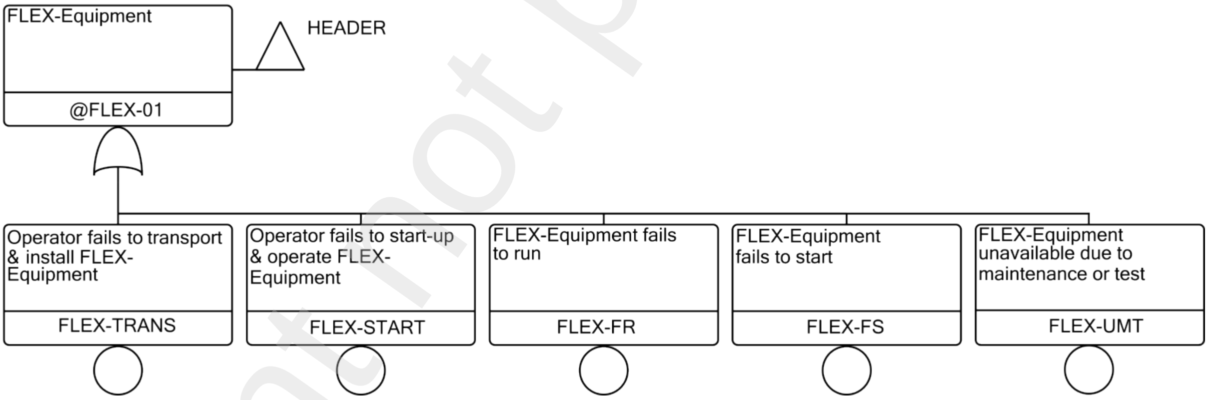

Figure 8: Example of the FLEX equipment FT modelling

4.3 DATA FOR FLEX EQUIPMENTS

Because the operating experience with FLEX equipment experience is practically non-existent (there are only equipment tests, but not in real conditions, and some integrated exercises), there is not a large collection of data on the failure rates of this equipment. Guidance NEI 16-06 (NEI, 2016b) proposes that each site that includes portable equipment in its PSA model use engineering judgment regarding failure rates. Failure rates for permanently installed equipment were also used, and a sensitivity study was performed to increase these failure rates by a factor of 10; the NRC agreed that the use of engineering judgment is acceptable for estimating parameter values under certain conditions, but also noted that failure rates for permanently installed equipment cannot be used for portable equipment, even when sensitivity analyses are performed. The NRC emphasizes the need for up-to-date data for risk and safety assessment in SPAR models and suggests a possible path forward based on EPRI's data collection (Lane, 2017).

In recent years, initiatives have been developed that have made a first estimation of the failure parameters of FLEX components. In 2020, Idaho National Laboratory develops Evaluation of Weakly Informed Priors for FLEX Data (Gentillon et al., 2020), this report is based on FLEX Equipment Data Collection and Analysis, PWROG-18043-P Revision 0 to obtain industry-wide failure probability and rate distributions for portable FLEX equipment. In 2021, the PWROG issued Revision 1 of PWROG-18043 with proprietary information, which provides FLEX equipment reliability parameters for use in PSA. In 2022, The PWROG released a non-proprietary version of the report PWROG-18043, with generic failure probabilities for portable FLEX equipment, PWROG-18042-NP (Degonish, 2022); the data included in this report are acceptable to the US NRC to support RI applications (NRC, 2022b) and is expected to be updated periodically to incorporate new operating experience data. This eliminates certain concerns that were associated with the: use of expert judgement; crediting spare equipment in lieu of equipment failure rates; use of permanently installed equipment failure rates; use of old data (NRC, 2022b). The procedure to obtain the data was summarized by Linthicum et al. (Linthicum & Powell, 2022), Table 8. Uncertainties still remain associated with maintenance or testing performed on FLEX equipment and Common Cause Failure (CCF) Parameters.

Table 8: FLEX equipment failure probabilities

Equipment	Failure Mode	
	Fail to Run 24 hours	Fail to Start
Portable Diesel Generator	2.47E-01	4.35E-02
Portable Combustion Turbine	4.46E-01	3.30E-02
Portable Diesel-Driven Pump	3.72E-01	3.38E-02
Portable Motor-Driven Positive Displacement Pump	3.74E-01	7.35E-03
Portable Diesel-Driven or Motor-Driven Air Compressor	6.76E-01	2.46E-02
Fire Protection System Diesel-Driven Pump	4.45E-02	2.17E-03

4.4 HUMAN RELIABILITY ANALYSIS APPLIED TO FLEX STRATEGIES

Current HRA analysis techniques have limitations when applied to FLEX strategies. Aspects such as transportation or connection of portable equipment are not addressed in existing HRA methods. In this case, engineering judgment is generally used to find the unknown Human Error Probabilities (HEP) value based on generic data from other industries. However, with this method, the uncertainty of its results from subjective evaluation can be very high. The main proposal from NEI, NRC and EPRI are:

- NEI suggested a simplified approach to give credit for portable equipment, developed simple decision trees to estimate the HEPs of FLEX strategies in which the headers are four factors: time margin; command and control; environmental factors; and equipment availability. The final HEP can be calculated by multiplying the base HEP and the value of the four factors (NEI, 2015).

- The NRC proposed expert judgment to support the FLEX HRA (NRC, 2020a). In addition, they are working on developing a new HRA method for FLEX (NRC, 2020b). In both cases they have consulted a panel of HRA analysts from the NRC and industry. Later, in 2022, The NRC presented IDHEAS-ECA (NRC, 2022a). This methodology can be applied to external events, low power and shutdown events, and events that require the use of FLEX strategies. It makes use of five macrocognitive functions: detection, understanding, decisionmaking, action execution, and interteam coordination. To calculate the HEPs, IDHEAS-ECA defines 20 performance-influencing factors (PIFs) in four context categories.
- EPRI conducted a review of procedures related to FLEX-like actions at several plants in the U.S. (EPRI, 2014). It discovered gaps in multiple tasks and approaches: Equipment transportation and installation; Environmental effects on execution (timing, execution, equipment availability and staffing); Organizational prioritization (Coordination, resource management); Procedures (detecting priorities); Synchronization (prioritization and availability of work teams); Execution in many steps (complex executions and decision making). As a result, it produced a reference document (EPRI, 2018), this is a guide based on examples and possible variations for the different scenarios: ELAP declaration; portable pump transportation, installation and actuation; and portable generator refueling. However, the authors highlight that questions remain about the suitability of HRA methods for addressing FLEX events (Ulrich et al., 2020). EPRI also modified their HRA calculator to facilitate modeling HRA for FLEX actions (NRC, 2022b).

In addition, other groups have addressed the problem of HRA for FLEX Strategies; Kim et al. (J. Kim, 2019; J. Kim et al., 2018) studied HRA for the Multi-barrier Accident Coping strategy (MACST). Hasan et al. (Hasan et al., 2018) calculated human error probabilities for the implementation of MACST during an extended SBO scenario in APR1400, and Duffey (Duffey, 2019) analyzed the dynamic human response and coping actions during a BDBEE with a time-dependent HRA approach. In addition to single-unit scenarios, Park et al. (J. Park et al., 2019) focused on human error issues in multi-unit HRAs. Park et al. (J. Park et al., 2021) modeled FLEX human actions for an ELAP scenario using the EMRALD software and introduced two different HRA approaches (1) procedure-based modeling and (2) PRA/HRA-based modeling. Later, Park et al. (J. Park et al., 2022) introduced PRIMERA-HRA method, which combines the two EMRALD modelling approaches. Finally, several authors have proposed the application of modified versions of SPAR-H approach to FLEX conditions and portable equipment. (G. Park et al., 2021; J. Park et al., 2019)Some HEPs results from these references are shown in Tables 9 and 10.

In the UPM model, the SPAR-H methodology has also been adapted to the conditions of FLEX strategies (Courtin et al., 2021) taking into account previous works adapting this approach to FLEX actions previously mentioned, (G. Park et al., 2021; J. Park et al., 2019) but also other modifications related with L2PSA, (J. Liu et al., 2016; Saint Germain et al., 2016; Wang, 2013a) fire scenarios, (K. Liu et al., 2018, 2019; Wang, 2013b) and other modifications proposed elsewhere (Laumann & Rasmussen, 2016; P. Liu et al., 2020, 2021). The obtained HEPs with the modified SPAR-H approach are shown in Table 11.

Table 9: Comparison of HEPs results for FLEX-DG

Author	Transport + Connection	Start-up + Operation	TOTAL HEP
(NEI, 2016b)	[1.02E-01, 5.00E-03]	-	-
(Son & Lim, 2017)	-	-	1.73E-02

(Shahinoor & Lim, 2017)	-	-	1.99E-02
(Hasan et al., 2018)	-	-	8.80E-03
(J. Kim et al., 2018)	1.37E-03	1.01E-03	6.23E-03
(J. Park et al., 2019)	2.00E-03	1.20E-02	1.40E-02
(J. Kim, 2019)	-	4.00E-02	-
(Ma et al., 2019)	3.00E-03	1.20E-02	1.50E-02
(Ryu et al., 2019)	-	-	[4.90E-01, 8.10E-01]
(NRC, 2020a)	3.00E-01	1.20E-01	4.20E-01
(NRC, 2020b)	1.00E-03	[1.00E-03, 1.00E-02]	1.00E-02
(J. Park et al., 2021)	5.00E-02	-	-
(G. Park et al., 2021)	3.01E-03	4.00E-04	3.42E-03
(J. Park et al., 2022)	7.40E-02	-	-

Table 10: Comparison of HEPs results for FLEX Pumps

Author	Transport + Connection	Start-up + Operation	TOTAL HEP
(Son & Lim, 2017)	-	-	6.16E-02
(Hasan et al., 2018)	-	-	8.90E-03
(Tabadar et al., 2019b)	1.39E-02	-	-
(J. Park et al., 2019)	2.00E-03	1.20E-02	1.40E-02
(J. Kim, 2019)	-	4.00E-02	-
(NRC, 2020a)	2.50E-01	1.40E-01	3.90E-01
(J. Park et al., 2021)	5.00E-02	-	-

Table 11: HEP used in UPM Model (modified SPAR-H)

Equipment	Transport + Connection	Start-up + Operation	TOTAL HEP
FLEX-DG	4.70E-02	6.00E-03	5.30E-02
FLEX-SGP	4.70E-02	4.54E-01	5.01E-01
FLEX-MUP	4.70E-02	1.35E-01	1.82E-01
FLEX-HCP	4.70E-02	1.35E-01	1.82E-01
DDP-FPS	Align to SGs	Start-up + Operation	
	1.00E-01	5.00E-02	1.5E-01

5 IMPACT OF FLEX STRATEGIES ON THE RISK REDUCTION

The total impact of the strategies on the full model is quantified through the variation of the CDF. The global results (ΔCDF in Table 12) show a reduction in the risk of situations leading to CD. This reduction (89.4%) is close to an order of magnitude, which shows the importance that this type of strategies can have in nominal power that are not fully related to the BDBEE. The variation in CDF, for each initiator, is shown in Table 13. Also, a comparison CDF results, including FLEX Strategies, found in the literature is presented in Table 14. The Anticipated Transient Without Scram (ATWS) scenario is not considered in the model as an initiating event, but it is considered as a possible sequence event within the initiators that require reactor trip.

Table 12: FLEX strategies impact on CDF.

CDF (1/y)	1.29E-05
CDF FLEX (1/y)	1.37E-06
ΔCDF (%)	**89.4%**

Table 13: CDF comparison.

L1PSA ET	**L1PSA Frequency (1/y)**	**Without FLEX strategies**		**With FLEX strategies**		**ΔCDF (%)**
		CDF (1/y)	**% Total CDF**	**CDF (1/y)**	**% Total CDF**	
GT	6.76E-01	7.39E-06	57.14	8.40E-07	61.54	-89%
LBLOCA	5.91E-06	1.15E-08	0.09	1.15E-08	0.84	0%
LC	4.82E-02	5.14E-07	3.97	6.08E-08	4.45	-88%
LCWA	1.80E-03	7.08E-10	0.01	6.21E-10	0.05	-12%
LDC-A	5.00E-04	1.79E-08	0.14	2.42E-09	0.18	-86%
LDC-B	5.00E-04	1.50E-08	0.12	1.78E-09	0.13	-88%
LNSW	2.00E-04	2.19E-09	0.02	2.32E-10	0.02	-89%
LOOP	3.11E-02	4.45E-07	3.44	3.57E-08	2.62	-92%
MBLOCA	1.50E-04	1.21E-07	0.94	2.90E-08	2.12	-76%
MSLB-DS	6.32E-03	7.54E-07	5.83	5.87E-08	4.30	-92%
MSLB-US	3.01E-04	4.15E-08	0.32	4.94E-09	0.36	-88%
SBLOCA	4.01E-04	1.65E-07	1.28	5.82E-08	4.26	-65%
SGTR	1.66E-03	3.46E-06	26.74	2.83E-07	20.73	-92%
CDF Total		**1.29E-05**		**1.37E-06**		**-89%**

Table 14: Comparison of CDF reduction including FLEX Strategies.

Author	ΔCDF		Reactor type
	LOOP/SBO	Overall	
(J.-S. Kim & Kim, 2021)	12%	9%	OPR1000
(J.-S. Kim & Kim, 2021)	73%	10%	APR1400
(Hakobyan & Nierode, 2017)		75%	PWR
(Lim, 2018)	(18-20)%		APR1400
(Ng, 2020)	(5-75)%		PWR
(Zhang & Ma, 2020)	64%		PWR
(Jabbari et al., 2020)	99%		VVER-1000
(Ma et al., 2019)	26%		PWR
(Son & Lim, 2017)	77%		APR1400
UPM (2023)	92%	89%	PWR

6 SENSITIVE ANALYSIS OF THE FLEX STRATEGIES

To study the impact of the FLEX strategies described in Section 2, it was decided to classify them into 4 groups, Table 15. Using this classification, the FLEX ET CDF has been calculated for each of the groups separately. The results are shown in Tables 16 and 17. The following conclusions can be obtained:

- Strategies 1 and 3 concentrate the largest risk reduction. The inclusion of FLEX-SGP and DDP-FPS decreases the probability of "AF+FLEX" header failure because there are two new independent options who allow inject to SGs. It also must be remarked that the better reliability of the DDP-FPS with respect to the FLEX-SGP is the main reason of this CDF reduction.
- Strategy 2, "Coolant injection to RCS", does not represent a significant risk reduction in this scenario, because the incorporation of passive thermal seals has greatly reduced the probability of seal leakage in the RCPs. However, it is important in SBLOCA (ΔCDF: -27.9%) and MBLOCA (ΔCDF: -10.7%). It should be noted that in some plants this is not an effective strategy due to low pump mass-flow rate and will only be useful for the seal LOCA.
- Strategy 4, "Alternate power supply and management", contributes to a lesser extent to risk reduction, and has only minimal importance in the LOOP-SBO scenario, since the probability of external power recovery is relatively high for the accident time evolution considered in this scenario. It may, however, be a very relevant strategy in a scenario without external power recovery, for example, an ELAP due to BDBEE.

It is important to note that these results are strongly dependent on HEPs and failure data from portable equipment, for both of which there is a large associated uncertainty. Therefore, it is highly recommended to perform a sensitivity analysis on these uncertainties.

Table 15: FLEX strategies.

ID	Description	Headers
Strategy 1	SGs coolant injection (FLEX-SGP + DDP-FPS + TDP-Manual)	• AF+FLEX • TDP-MANUAL
Strategy 2	RCS coolant injection (Long term RCS inventory Control /Alternate RCS boration) (FLEX-MUP)	• FLEX-MUP • FLEX-MUP-RWST
Strategy 3	RWST inventory control (FLEX-HCP, DDP-FPS-RWST)	• RWST-FLEX
Strategy 4	Alternate power supply and management (FLEX-DG + LBS)	• LB+FLEX • LBS • R-EX+R-DG

Table 16: FLEX strategies contribution on the risk reduction.

ID	Strategy	**TOTAL**	
		CDF (1/y)	ΔCDF (%)
L1PSA	Model without FLEX	1.29E-05	-
Strategy 1	SGs coolant injection	6.41E-06	-50.3%
Strategy 2	RCS coolant injection	1.28E-05	-0.5%
Strategy 3	RWST inventory control	6.28E-06	-51.4%
Strategy 4	Alternate power supply and management	1.29E-05	-0.1%
L1PSA-FLEX	Model with FLEX	1.37E-06	-89.4%

Table 17: FLEX strategies contribution on the risk reduction.

Initiator	**Strategy 1**		**Strategy 2**		**Strategy 3**		**Strategy 4**	
	CDF (1/y)	**ΔCDF (%)**	**CDF (1/y)**	**ΔCDF (%)**	**CDF (1/y)**	**ΔCDF (%)**	**CDF (1/y)**	**ΔCDF (%)**
LBLOCA	1.15E-08	0.0%	1.15E-08	0.0%	1.15E-08	0.0%	1.15E-08	0.0%
MBLOCA	1.21E-07	0.0%	1.08E-07	-10.7%	4.17E-08	-65.5%	1.21E-07	0.0%
SBLOCA	1.62E-07	-1.8%	1.19E-07	-27.9%	1.07E-07	-35.2%	1.65E-07	0.0%
GT	1.73E-06	-76.6%	7.38E-06	-0.1%	5.06E-06	-31.5%	7.39E-06	0.0%
LC	1.06E-07	-79.4%	5.14E-07	0.0%	3.65E-07	-29.0%	5.14E-07	0.0%
MSLB-DS	7.01E-07	-7.0%	7.54E-07	0.0%	9.80E-08	-87.0%	7.54E-07	0.0%
MSLB-US	3.40E-08	-18.1%	4.15E-08	0.0%	1.05E-08	-74.7%	4.15E-08	0.0%
LCWA	6.21E-10	-12.9%	7.13E-10	0.0%	7.13E-10	0.0%	7.13E-10	0.0%
SGTR	3.46E-06	0.0%	3.46E-06	0.0%	2.83E-07	-91.8%	3.46E-06	0.0%
LNSW	4.25E-10	-79.8%	2.10E-09	0.0%	1.48E-09	-29.5%	2.10E-09	0.0%
LDC-A	2.97E-09	-83.4%	1.79E-08	0.0%	1.37E-08	-23.5%	1.79E-08	0.0%
LDC-B	2.58E-09	-82.8%	1.50E-08	0.0%	1.08E-08	-28.0%	1.50E-08	0.0%
LOOP	8.40E-08	-80.3%	4.26E-07	-0.2%	3.01E-07	-29.5%	4.16E-07	-2.6%

7 CONCLUSIONS

The main conclusions drawn from the study are summarized in the following points:

- New ETs have been created in the generic SPAR-CSN model to model the Post-Fukushima FLEX strategies, including human actions and equipment, making it possible to quantify the risk reduction.
- The quantification of the new ETs, including the FLEX strategies, shows a decrease in the CDF close to 90%. This reduction is directly related to the new or modified headers related to these FLEX strategies. These results are similar to other works on FLEX modeling in PSA models.
- The incorporation of FLEX strategies in the L1PSA models is recommended, including uncertainty and sensitivity analysis.
- The sensitivity study of the FLEX strategies has determined that, for this particular scenario and NPP; the strategies related to the injection of coolant in the steam generators have the greatest contribution in the relative risk reduction.

It is important to note that the results obtained in this work are only valid for internal events at nominal power. It is highly recommended to extend the study of the impact of FLEX strategies to other different and/or more complex scenarios, such as low power and shutdown conditions (LPSD); external events (earthquakes, floods, fires, etc.); ELAP; LUHS; and BDBEE.

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