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Application of FLEX Strategies to Cope with a Station Blackout (SBO) Situation

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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 are a set of mitigation strategies that reduce risks associated with conditions of the previously mentioned BDBEE. They are based on the incorporation of various enhancements, including portable equipment (instrumentation, diesel generators, diesel pumps, etc.) and procedures that provide multiple means of power and water supply to support key safety functions.

These aforementioned FLEX strategies are also useful to avoid core damage in sequences at nominal power due to internal events in *"sunny days"*. Therefore, these FLEX strategies could be incorporated in the *Level 1 Probabilistic Safety Assessment* (L1PSA) at power to analyse their impact on core damage frequency (CDF), so these procedures and equipment should be included in the plant-specific PSAs in order to quantify the plant risk reduction. This work quantifies the impact of FLEX strategies to Loss of Offsite Power (LOOP) sequences by using a standardized generic model (3 loops, PWR-WEC) developed by the Technical University of Madrid (UPM) in collaboration with the Spanish 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.

1 INTRODUCTION

Following the incidents of September 11 in 2001 and Fukushima Dai-ichi in March 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 NEI 12-06, where the term "FLEX Strategies" is defined for the first time [1]. This document defines FLEX as 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, as a consequence of a BDBEE, through alternative human actions and the use of portable equipment, stored inside or outside the facility.

The L1PSA model developed under the SPAR-CSN project can serve as an example of how to incorporate these strategies (Section 3) and how they affect the risk of plant damage (Section 4).

2 SPAR-CSN 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 (NPP) 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 Technical University of 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 [2,3,4]. 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 [5].

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 PSA level 1 models.

3 LOOP EVENT TREE MODELLING

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 impact of FLEX strategies in a LOOP scenario at nominal power.

In order to understand the modifications introduced by the FLEX strategies, the LOOP event tree (ET) of the generic SPAR-CSN model without FLEX strategies is presented first (Figure 1), later the LOOP ET will be quantified. This ET includes the following headers:

- Z: Reactor protection system.
- DG: Emergency power from emergency diesel generator (EDG) EDG-A or EDG-B.
- AF: Auxiliary feedwater system (AFWS).
- TS: Passive thermal seals of reactor coolant pumps (RCPs).
- LS: Flow rate of RCPs seals leakage (Seal LOCA).
- LB: Power supply to battery charges by means of DG-SBO.
- R-EX: Offsite power recovery.

Depending on the fulfillment of the success criteria of the headers described above, the transient may result in Safe Shutdown (S), Core Damage (CD) or transfer to another transient. The following situations can be found in Figure 1:

1) Emergency Diesel operation after LOOP would lead the plant to a *generic transient* due to power recovery (GT-LOOP), sequence 1 (S1).
2) In the event of a failure of the EDGs, the plant would enter *a Station Blackout* (SBO) situation where it would require the operation of the passive thermal seals and the operation of the SBO diesel generator or a recovery of the external power in less time than it would take for the batteries to deplete, (S2 to S4).
3) In any situation where the AFWS or passive thermal seals fails, there will be an inventory leakage from the Reactor Coolant System (RCS) leading to *Small Break Loss of Coolant Accident* (SBLOCA) or CD situation depending on whether or not the external AC power is recovered in time, (S5 to S10).
4) Failure of the reactor protection system would bring the plant into an *anticipated transient without scram* (ATWS) situation, (S11).

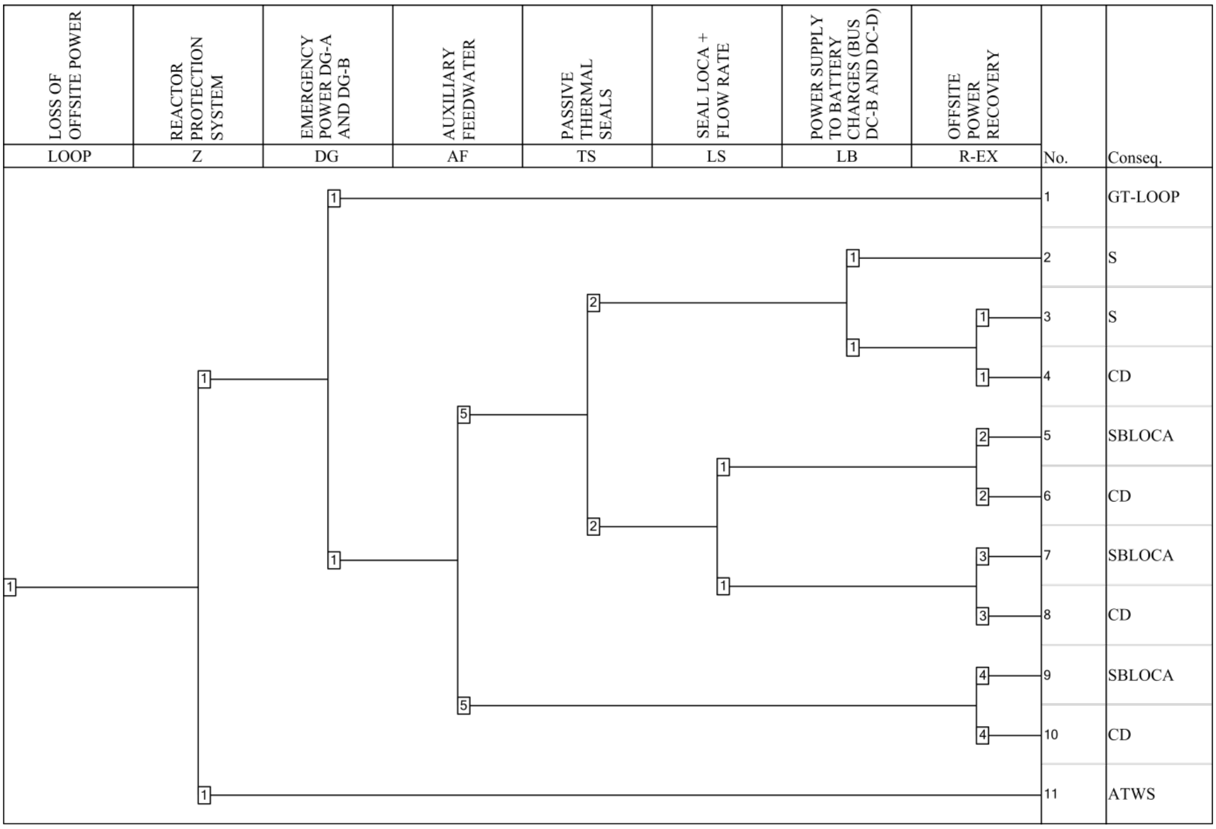

Figure 1: LOOP-SBO event tree without any FLEX strategy.

The inclusion of FLEX strategies in the above ET has been done considering a series of specific actions and equipment. These strategies are:

- Coolant injection to the SGs by a low pressure portable diesel pump (FLEX-SGP).
- Coolant injection to the SGs by the diesel-driven pump of the fire protection system (DDP-FPS).
- Coolant injection to the RCS by a medium/high pressure portable diesel pump (FLEX-MUP).
- Supply of AC power by the portable diesel generator (FLEX-DG).
- DC load shedding to increase battery life.
- Manual operation of turbine-driven AFW pump (TDP-AFW) after DC loss.

The above FLEX strategies are not necessarily included in all plants. Some strategies may require system design changes and, in addition, not all possible strategies are included in the *FLEX Support Guidelines* (FSG) [6]. The FSG are accessed through the *Emergency Operating Procedures* (EOPs), like ECA-0.0, FR-H.1, FR-C.1 or FR-C.2.

Additionally, although not considered a FLEX strategy as such, the recovery of at least one EDG has been added. This is despite the fact that the probability of recovery in the short term is low and depends on the EDG failure type.

The addition of the above mentioned FLEX strategies configures the new LOOP ET (Figure 2); this event tree includes the following new (or modified) headers:

- AF+FLEX: Residual heat removal through the secondary with diesel pumps FLEX-SGP or DDP-FPS or TDP-AFW.
- FLEX-MUP: Coolant injection into the RCS with the FLEX-MUP diesel pump.
- LB+FLEX: Power supply to loads (DC-B/C buses) from DG-SBO or FLEX-DG.
- LBS: DC load shedding of non-essential loads from batteries, header.
- R-EX+R-DG: External AC power recovery or recovery of any EDG.
- TDP-MANUAL: Manual operation of the TDP-AFW.

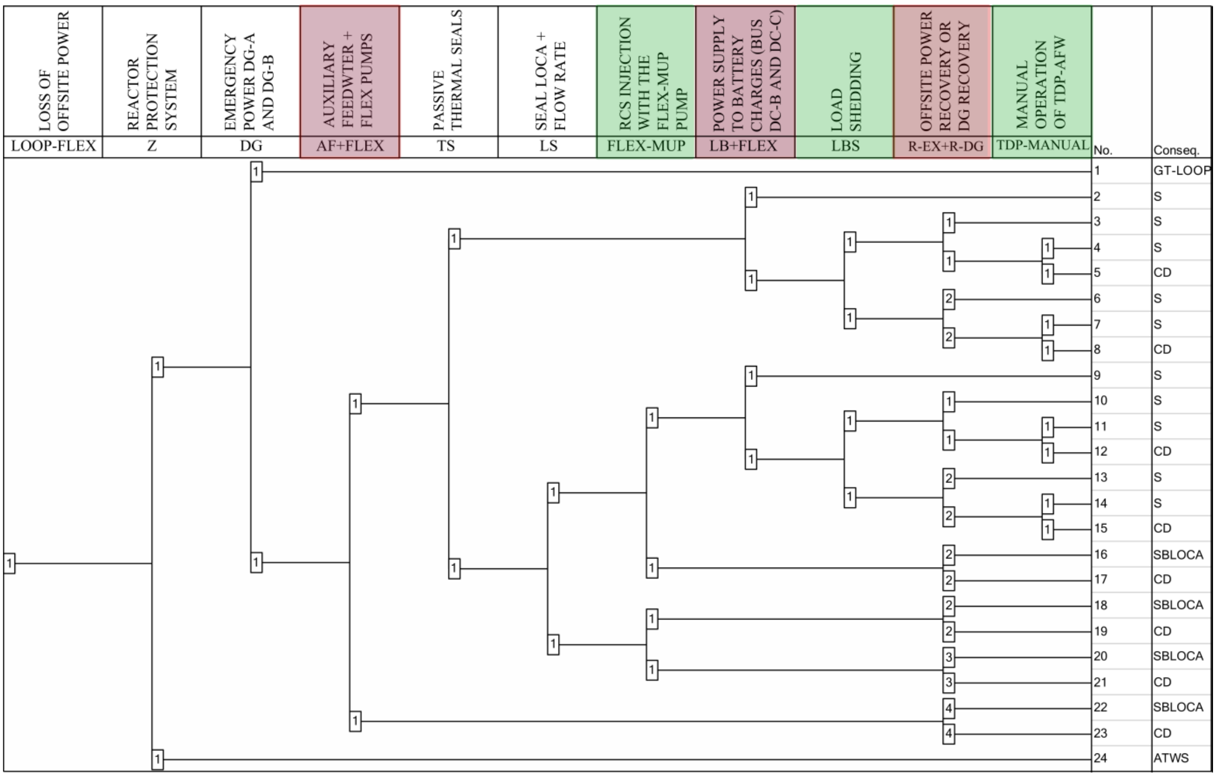

Figure 2: LOOP-SBO ET with FLEX strategies headers. Modified in red, new ones in green.

Considering this new ET configuration, a new situation can be distinguished in addition to those already described above in the LOOP-SBO. In this new ET, 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 inventory loss of the RCS after the failure of the passive thermal seals.

Besides, the incorporation of FLEX strategies through the actions and equipment mentioned above will result in a reduction in the CDF (see Section 4).

4 IMPACT OF FLEX STRATEGIES ON THE RISK REDUCTION

As discussed in the previous section, the new LOOP-SBO ET of the SPAR-CSN model results in a reduction in the CDF. This reduction was evaluated by quantifying the LOOP-FLEX ET. 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) have been considered in the modeling of the fault trees (FT).

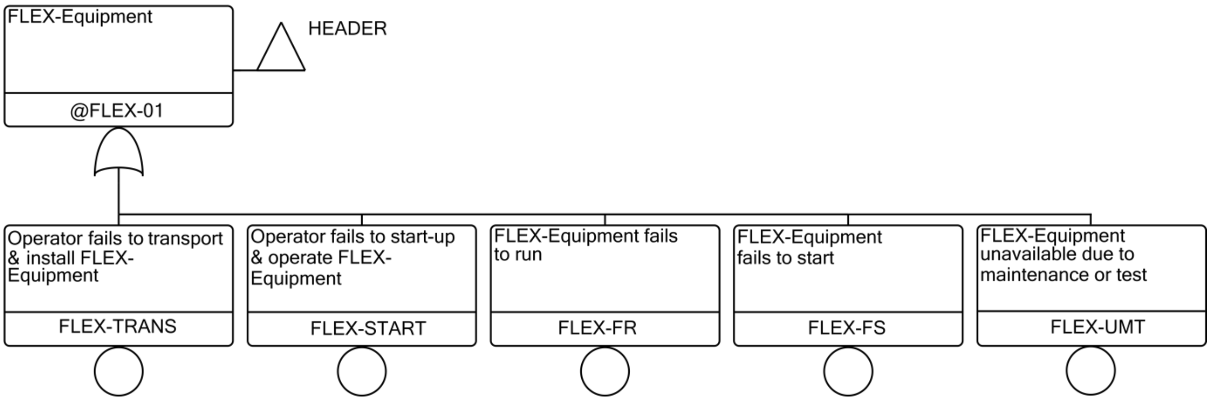

Figure 3: Example of the FT FLEX modelling.

Because the operating experience of FLEX equipment is relatively small, there is not a large collection of data on the failure rates of this equipment, however; there are initiatives that have made a first estimation of the failure parameters of FLEX components depending on whether the failure is in startup or in operation (24 hours mission time) [3]. Similarly, although there is consensus that current human reliability methodologies are not entirely adequate to quantify HFE in FLEX scenarios, there are some estimates that allow us to get an idea of the orders of magnitude of the Human Error Probabilities (HEP) [2], [7].

Tables 1 & 2 show the quantification of the LOOP ET with and without FLEX strategies. The results (ΔCDF in Table 1) show a reduction in the risk of LOOP situations leading to CD. These results are consistent with other works on FLEX modeling in PRA models [17]. This reduction (87.7%) is close to one order of magnitude, which shows the importance that this type of strategies can have in nominal power sequences not completely related to the BDBEE.

In addition to this, after the analysis of the LOOP-FLEX ET sequences, it is observed that the dominant damage sequence corresponds to sequence number 1, with success actuation of EDGs, which transfers to the generic transient (GT-LOOP), but with AF+FLEX and F&B headers failure, with 87%. This sequence has associated, and shares with other sequences, the AF header, whose failure probability value has been reduced with the introduction of the FLEX strategies. The conjunction of these features is responsible for the CDF reduction.

It is important to understand in detail where such risk reduction comes from. For this, it is useful to quantify the reduction in the failure probabilities of the headers after the introduction of the FLEX strategies (Table 2). Also, a quantitative sensitivity analysis of the FLEX strategies has been carried out in Section 5.

Table 1: Impact of FLEX strategies on LOOP CDF.

CDF LOOP (1/y)	4.34E-07
CDF LOOP-FLEX (1/y)	5.35E-08
ΔCDF (%)	**87.7%**

Table 2: Headers failure probabilities of LOOP and LOOP-FLEX ETs.

ET-LOOP HEADERS	**Fail Prob.**	**ET-LOOP-FLEX HEADERS**	**Fail Prob.**
Reactor Protection System (Z)	2.76E-06	Reactor Protection System (Z)	2.76E-06
Emergency Power DG-A & DG-B (DG)	2.13E-03	Emergency Power DG-A & DG-B (DG)	2.13E-03
Auxiliary Feedwater (AF)	**4.63E-02**	Auxiliary Feedwater + Flex Pumps (AF+FLEX)	**1.30E-03**
Passive Thermal Seals (TS-SBO)	5.52E-02	Passive Thermal Seals (TS-SBO)	5.52E-02
Flow rate of seal leakage (LS)	2.50E-03	Flow rate of seal leakage (LS)	2.50E-03
		RCS Injection with the FLEX-MUP Pump (FLEX-MUP)	**5.45E-01**
Power Supply to Battery Charges (Bus DC-B and DC-C) (LB)	**7.06E-03**	Power Supply to Battery Charges (Buses DC-B/C) (DG-SBO + FLEX-DG)	**2.32E-03**
		Load Shedding (LBS)	**1.00E-02**
Offsite Power Recovery (R-EX)	**[1.32E-03; 4.70E-03]**	Offsite Power Recovery or DG Recovery (R-EX+R-EDG)	**[6.27E-04; 4.28E-03]**
		Manual Operation of TDP-AFW (TDP-MANUAL)	**5.00E-01**

5 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 the following 4 groups:

Table 3: FLEX strategies considered.

R-DG	Diesel generator recovery (R-DG)
Strategy 1	SGs coolant injection (FLEX-SGP + DDP-FPS + TDP-Manual)
Strategy 2	RCS coolant injection (FLEX-MUP)
Strategy 3	AC power supply and load shedding (FLEX-DG + LBS)

Using this classification, the LOOP-FLEX ET CDF has been calculated for each of the groups separately and for different combinations between them. The results are shown in Table 4. It should be noted that the combinations of FLEX strategies do not include the recovery of EDG (R-DG), the reason being that this action is not considered a FLEX strategy.

Table 4: Contribution of the different FLEX strategies on the risk reduction.

Strategy	**CDF (1/y)**	**ΔCDF (%)**
ET-LOOP (Generic)	4.34E-07	-
ET-LOOP W/ R-DG	4.27E-07	**1.6%**
ET-LOOP W/ Strategy 1	6.41E-08	**85.2%**
ET-LOOP W/ Strategy 2	4.33E-07	**0.2%**
ET-LOOP W/ Strategy 3	4.19E-07	**3.5%**
ET-LOOP W/ Strategies 1-2	6.32E-08	**85.4%**
ET-LOOP W/ Strategies 1-3	5.54E-08	**87.2%**
ET-LOOP W/ Strategies 2-3	4.18E-07	**3.7%**
ET-LOOP-FLEX	5.35E-08	**87.7%**

The following conclusions can be obtained from Table 4:

- Strategy 1, "Coolant injection to SGs", concentrates the largest risk reduction. The inclusion of FLEX-SGP and DDP-FPS decreases the probability of “AF+FLEX” header failure because in a LOOP-SBO situation the failure of this header depends strongly on the failure probability of the TDP-AFW.
- 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. Nevertheless, it is a strategy that should not be dismissed and it is advisable to study its impact in other scenarios, e.g., ELAP with RCP thermal seals failure or sequences with HPSI pumps failure during recirculation at high pressure.
- Strategy 3, "AC power supply and load shedding", contributes to a lesser extent to risk reduction, 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 human error probabilities (HEP) 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.

6 CONCLUSIONS

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

- It has been created a new LOOP ET in the generic SPAR-CSN model that allows including the Post-Fukushima FLEX strategies, including actions and equipment, making possible to quantify the risk reduction in these situations.
- The quantification of the new LOOP ET, 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 PRA models.
- The incorporation of FLEX strategies in the L1PSA models is recommended, including an uncertainty 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 LOOP and SBO scenarios 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.

ACKNOWLEDGMENTS

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