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Analysis of the Impact of some Post-Fukushima Improvements on Design Extension Condition Sequences

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ABSTRACT

After the Fukushima accident, Nuclear Power Plants (NPPs) were required to demonstrate their reliability by increasing their safety provisions and equipment to mitigate accidents. These requirements must cover equipment, procedure improvements, and regulatory development. One of the most important actions has been the introduction of the analysis of the Design Extension Conditions (Multiple Failure Conditions outside the design basis envelope, DEC) into the design requirements of NPPs to further improve safety.

On this subject, in the framework of the SPAR-CSN project to create a Standardized Plant Analysis Risk (SPAR) model for Spanish NPPs, a novel methodology has been developed to identify sequences that are outside the design basis but not reaching fuel damage, DEC-A, making use of the PSA level 1 model for a generic plant (3-loop PWR Westinghouse design). Using this method, we have been able to identify the DEC-A sequences with high relative risk by comparing their frequencies with their corresponding DEC-B (sequences with fuel damage).

As shown in this study, the addition of Post-Fukushima improvements reduces the relative risk of the DEC sequences in which these are involved.

1 INTRODUCTION

The Fukushima accident has led the nuclear industry and regulatory bodies to look for enhancements in order to increase the safety of NPPs against beyond design basis events. Following the determination of lessons learned from this accident, new on-site actions have been developed, focused on "adding capabilities to maintain key plant safety functions following a large-scale natural disaster; updating evaluations on the potential impact from seismic and flooding events; new equipment to better handle potential reactor core damage events; and strengthening emergency preparedness capabilities" [1], such as FLEX strategies or Passive Thermal Shutdown Seals (PTSSs). In addition, new regulatory requirements have been accomplished such as the analysis of the so-called Design Extension Conditions (DEC), as a part of the Design Basis Envelope (DBE).

The development of the DEC analysis is progressing rapidly both nationally and internationally. Nevertheless, current practices are not yet fully consistent with other elements of DBE, and the process of identification and selection of these specific conditions is still under discussion. Current practices/guidelines indicate that "the selection of events to be analyzed shall be justified on the basis of deterministic and probabilistic arguments and of engineering judgment" [2], which generally points at the use of the Probabilistic Safety Assessment (PSA) models as a tool for the DEC identification process.

Following this purpose, the paper shows a developed PSA-based methodology for DEC-A identification, as well as the results obtained after the application of this methodology to the level 1 PSA model of the SPAR-CSN project (Section 3). In addition, the present study includes the evaluation of the implementation in the PSA model of post-Fukushima enhancements in DEC sequences, in particular the PTSSs (Section 4), in order to provide a more comprehensive view of the safety improvement in NPPs.

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 NPP risks and can be seen as an enhancement of the regulatory practice.

On this regard, the Spanish 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 development 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 [3,4,5]. 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 [6].

Regarding 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 designing a suitable PSA-based methodology for DEC sequence identification. In addition, an example of the impact of the post-Fukushima improvements on DEC sequences has been included, focusing on the implementation of the PTSSs.

3 DEC-A IDENTIFICATION METHODOLOGY AND APPLICATION TO SPAR-CSN MODEL

This section shows the DEC-A sequence identification methodology developed by UPM and CSN, as well as its application to the PSA model of the SPAR-CSN project. The Method, composed of 11 steps (see Figure 1), is described below:

S1 Select an Initiating Event (IE) from the list of IEs covered in the PSA model.

S2 Select Sequences from the Event Tree (ET) of the IE with at least 1 failed header (SEQ).

S3 Identify SEQ leading to a safe state (S):
- These are candidates to be DEC-A sequences (i.e. sequences where multiple failures occur but leading to a safe state).
- Tag each identified sequence with "DEC-A" in the code (RiskSpectrum™) for the quantification process.

S4 From each sequence tagged as DEC-A, identify all the sequences with additional failures that lead to Core Damage (CD):
- These are candidates to be DEC-B-related sequences of the tagged DEC-A sequence.
- Tag each identified sequence with "DEC-B" in the code (RiskSpectrum™) for the quantification process.

S5 Quantify the frequency of every DEC-A tagged sequence, "DEC-A_freq". This step will provide a sorted list, which is helpful to the subsequent steps of the method.

Recurrent application of steps S1 to S5 allows to obtain a complete and sorted list of DEC-A sequences of the PSA model in conjunction with their related DEC-B.

S6 Apply a DEC-A frequency truncation criterion for sequence list reduction. The truncation criterion depends on the analysis target: a lower frequency limit requires the analysis of a larger set of DEC sequences.

S7 Quantify the accumulated frequency of the DEC-B sequences related to each DEC-A sequence, "DEC-B_freq" (Eq. 1). The method also postulates the use of the Conditional Core Damage Probability of each DEC sequence, "$CCDP_{DEC}$" (Eq. 2), as Figure of Merit (FoM) for every element of the collapsed list.

$$\text{DEC-B\_freq} = \sum_{i=1}^{n} \text{Frequency}_i^{\text{DEC-B}} \tag{1}$$

$$\text{CCDP}_{\text{DEC}} = \frac{\text{DEC-B\_freq}}{\text{DEC-A\_freq} + \text{DEC-B\_freq}} \tag{2}$$

S8 Group similar DEC-A sequences and remove low-risk ones, DEC-B_freq < p0 or $CCDP_{DEC}$ < p1, and sequences covered by the Deterministic Safety Analysis (DSA). The outcome would be a collapsed list of the most important DEC-A sequences by risk and their accumulated DEC-B-related frequency.

S9 Add new sequences in terms of other eventual criteria not considered up to now (e.g. Large Early Release Frequency (LERF), Releases, Regulations, etc.)

S10 Apply steps S1 to S9 to other PSA models such as Fire protection, Spent Fuel Pool (SFP), External events, Low Power and Shutdown (LPSD), etc.

S11 Add new sequences in terms of other sources of DEC-A identification, such as Dynamic PSA, Operating Experience, Expert Judgment, etc.

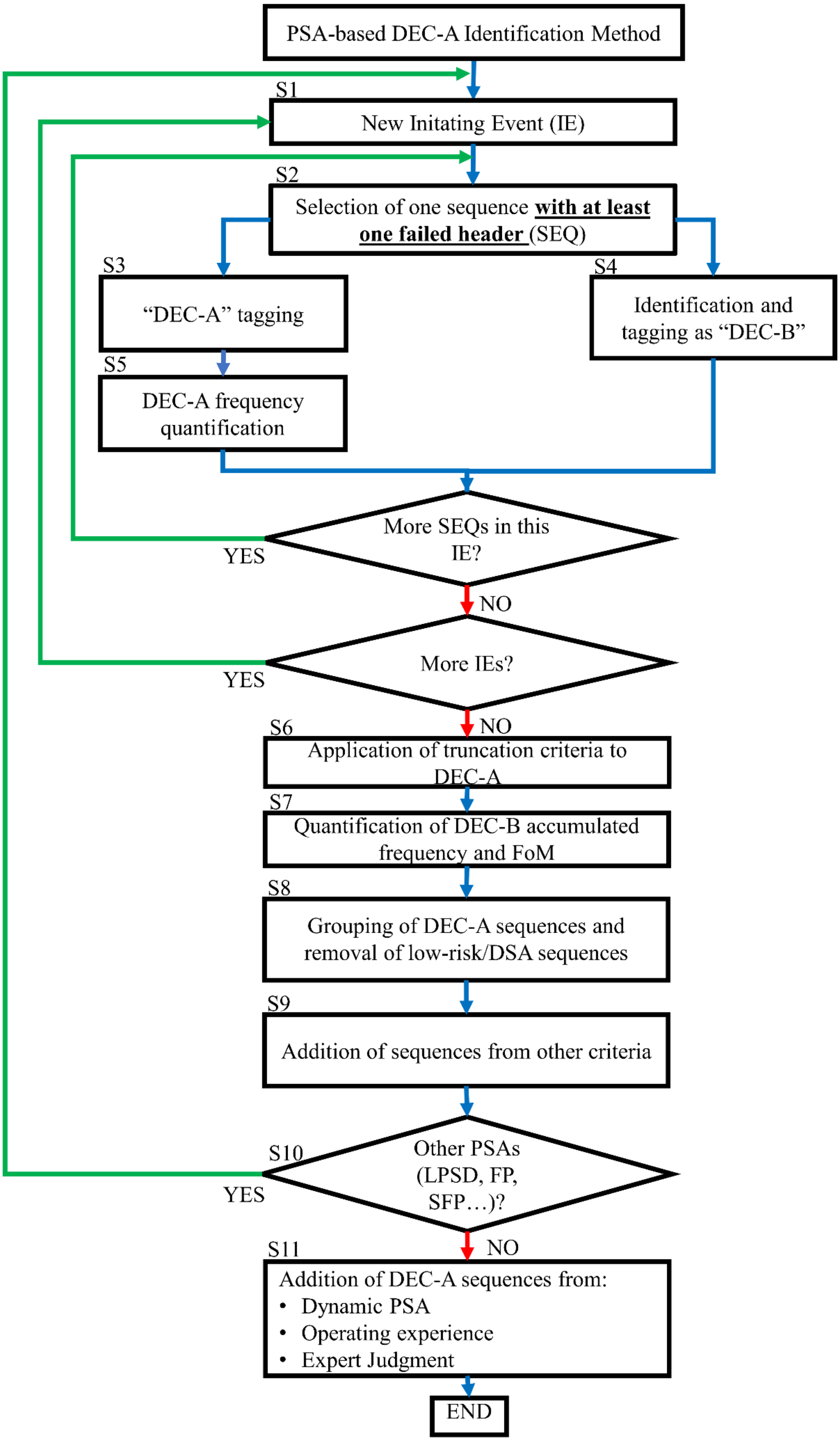

Figure 1: Flowchart of the PSA-based DEC-A identification method.

The application of the methodology to the SPAR-CSN PSA model resulted in a tentative list of DEC-A sequences with their frequency and FoM which represent their relative risk. This is comparable with current DEC lists developed by regulatory bodies.

Following the description of the methodology, the steps S1 to S11 of the method have been implemented through the following stages:

1. Steps S1 to S5 allowed to obtain 182 DEC-A sequences as sequences with multiple failures which lead to a safe state. In a subsequent step, the initial list of 182 sequences was reduced to 69 sequences after the application of a frequency truncation criteria of 1.0E-08 1/y (Step S6).
2. Following Step S7, the DEC-B sequences related to the reduced list of DEC-A have been quantified in order to obtain the FoM DEC-B_Freq. and $CCDP_{DEC}$.
3. Step 8, related to the elimination and grouping of sequences, was applied to the reduced list of 69 elements. In this process, 7 sequences were eliminated because they were analyzed in the DSA and additional 3 low-risk sequences (DEC-B_Freq. < 1.0E-09 1/y and $CCDP_{DEC}$ < 1.0E-04) sequences were eliminated, providing a list of 59 DEC-A sequences. Finally, some of the remaining sequences were grouped by similarity, resulting in a new collapsed list of 10 DEC-A sequences.
4. Through steps S9 to S11, 4 sequences were added, all of them by expert's judgment. The reason has been the lack of other criteria or PSA to sequences addition.

The outcome of the final stage is Table 1, which shows 14 DEC-A sequences sorted by cumulative DEC-B frequency, "DEC-B_Freq.". To make the phenomenology of the sequences of Table 1 clearer, a more in-depth description of the sequences is included below:

D1 Total Loss of Feed Water (TLFW) with successful Feed & Bleed (F&B) action.
D2 Small Break Loss of Coolant Accident (SBLOCA) caused by a Stuck-open pressurizer relief valve after a Steam Generator Tube rupture (SGTR) with actuation of the High-Pressure Safety Injection System (HPSIS) both in injection and recirculation modes.
D3 SBLOCA caused by a Stuck-open pressurizer relief valve after a Steam Line Break (SLB) with actuation of HPSIS both in injection and recirculation modes.
D4 SBLOCA/MBLOCA with failure to cooldown and depressurize the Reactor Cooling System (RCS) and actuation of HPSIS both in injection and recirculation modes.
D5 Seal LOCA (SLOCA) consequential of a System Blackout (SBO) with offsite power recovery.
D6 SGTR consequential of a SLB with actuation of HPSIS and successful cooldown and depressurization of RCS.
D7 Loss of the Component Cooling Water System (LCCWS) with successful RCP seals injection by the Hydrostatic Test Pump (HTP).
D8 Anticipated Transient Without SCRAM (ATWS).
D9 SGTR with Steam Generator (SG) isolation failure, actuation of HPSIS, and manual Bleed action.
D10 SBLOCA/MBLOCA with HPSIS actuation failure and successful cooldown and depressurization of RCS.
D11 Multiple SGTR (MSGTR).
D12 Boron Dilution.
D13 Loss of the Residual Heat Removal System (RHRS).
D14 Loss of Spent Fuel Pool (SFP) cooling.

It is important to make it clear the comparative purpose of the last column of Table 1; this represents the appearance of each DEC-A sequence in other current DEC lists found in the references [1,7,8,9,10].

Table 1: List of DEC-A sequences identified in the SPAR-CSN model.

No.	Sequences	DEC-A_Freq. (1/y)	DEC-B_Freq. (1/y)	$CCDP_{DEC}$	Included on any DEC list?
D1	TLFW + Successful F&B performance	5.8E-05	**7.8E-06**	**1.2E-01**	Yes
D2	SGTR + SBLOCA + HPSIS success during injection and recirculation	3.4E-06	**3.3E-06**	**4.9E-01**	**No**
D3	SLB + SBLOCA + HPSIS success during injection and recirculation	2.1E-05	**1.4E-06**	**6.0E-02**	**No**
D4	SBLOCA/MBLOCA + RCS cooldown and depressurization failure + HPSIS success during injection and recirculation	1.6E-06	**2.6E-07**	**1.4E-01**	**No**
D5	SBO + SLOCA + offsite power recovery	7.3E-05	1.3E-07	1.8E-03	Yes
D6	SLB + SGTR + HPSIS success and RCS depressurization	4.8E-05	1.1E-07	2.3E-03	Yes
D7	LCCWS + success in RCP seals injection by HTP	1.9E-07	6.4E-08	2.5E-01	Yes
D8	ATWS	1.9E-06	5.7E-08	2.9E-02	Yes
D9	SGTR + SG isolation failure + successful F&B action (automatic injection)	1.8E-07	2.4E-08	1.2E-01	Yes
D10	SBLOCA/MBLOCA + failure of HPSIS + successful cooldown and depressurization of the RCS	3.3E-08	1.8E-08	3.5E-01	Yes
D11	MSGTR				Yes
D12	Boron Dilution				Yes
D13	Loss of RHRS				Yes
D14	Loss of SFP cooling				Yes

DEC-A sequences with the highest relative risk of the SPAR-CSN model are marked in red in Table 1. The high value DEC-B_Freq and $CCDP_{DEC}$ for sequences, D1, D2, D3, and D4 is due to the dependency between human actions, modelled as part of the Human Reliability Analysis (HRA) of the PSA model.

Sequences D2, D3, and D4, are not included in any published DEC list, and, despite being 3 of the 4 DEC-A sequences of the model with the highest risk ($CCDP_{DEC}$ > 1.0E-02 and DEC-B_Freq > 1.0E-07 1/y). This reveals the potential of the use of PSA-based methodology to identify DEC-A sequences missed by DSA.

Finally, relative risk of sequences D8, D9, and D10; included in Table 1, may be reduced by implementing other modeling assumptions (Evolution of the Moderator Temperature Coefficient (MTC) between Beginning of Cycle (BOC) and End of Cycle (EOC)) or implementation of new human actions or equipment currently included at NPPs (implementation of motor-operated RV-line isolation valve, “fast cooldown” beyond 55 K/h).

4 IMPACT OF THE IMPLEMENTATION OF THE PASSIVE THERMAL SHUTDOWN SEAL (PTSS) ON THE RISK REDUCTION

As an example of the impact of Post-Fukushima equipment improvements on nuclear power plant safety, the implementation of Passive thermal Shutdown Seals (PTSSs) into the SPAR-CSN model previously described has been analyzed.

The design and installation of Passive Thermal Shutdown Seals (PTSSs) have been one of the improvements introduced in NPPs since the Fukushima-Daiichi accident. This equipment is especially useful to Station Blackout (SBO) or Extended Loss of Alternating Current Power (ELAP) type accidents and loss of safety support systems related to RCP seals. In these conditions, when the RCPs seals fail due to the loss of the coolant injection, PTSSs actuate to prevent inventory losses and the subsequent release of radioactive material into the containment. For this reason, the model for PTSSs has been introduced in LOOP/SBO and LCCWS Event Trees (ET). The modelling of this device causes a Relative risk reduction (ΔCDF) of 3% in the Core Damage Frequency of the entire SPAR-CSN PSA level 1 model; the results are shown in Table 2. The main reason for the low ΔCDF value is the fact that the main risk contribution comes from human actions and the dependency modelled between them.

Table 2: Impact of PTSSs in the SPAR-CSN model CDF.

SPAR-CSN Model CDF without PTSSs (1/y)	1.33E-05
SPAR-CSN Model CDF with PTSSs (1/y)	1.29E-05
ΔCDF (%)	3%

After the implementation of PTSSs, the methodology for DEC-A identification, described in section 3, is applied again, with the outcome shown in Table 3.

Table 3: List of new DEC-A sequences identified in the SPAR-CSN model with PTSSs.

Sequences	**DEC-A_Freq. (1/y)**	**DEC-B_Freq. (1/y)**	**$CCDP_{DEC}$**
SBLOCA/MBLOCA + Failure to depressurize RCS+ Success on HPSIS during injection and recirculation	8.8E-07	1.2E-07	1.2E-01
SBO + offsite power recovery	7.6E-05	5.3E-08	7.0E-04
SBO + SLOCA + offsite power recovery	4.0E-06	3.7E-08	9.1E-03
LCCWS + success of PTSSs or RCP seals injection by HTP	2.6E-07	7.2E-10	2.8E-03

The sequences shown in Table 3 may be described as:

- SBLOCA/MBLOCA with failure to cooldown and depressurize the RCS and actuation of HPSIS during injection and recirculation modes. The reduction in the relative risk of this sequence is due to the reduction in the frequency of LOCA occurrence as a consequence of other transients, such as LOOP, obtained as a result of PTSSs actuation.
- SBO with offsite power recovery. This sequence describes a scenario in which the PTSSs actuation prevents coolant leakage from the RCS under SBO conditions.
- SLOCA consequential of SBO with offsite power recovery. The risk of this sequence decreases because the PTSSs must fail to reach this situation.
- LCCWS with success of PTSSs or RCP seals injection by the HTP. In this sequence, PTSSs actuation prevents the leakage of coolant through the RCPs after the RCP seal injection fails, reducing its relative risk to achieve fuel damage.
  This sequence has been the most affected by this improvement, achieving a risk reduction of 1/100 times the previous value.

Following this structure, future works will analyze other post-Fukushima improvements, such as Load Shedding, Portable equipment implementation, and manual operation of the Turbine-Driven Pump of the Auxiliary Feedwater System, etc.

5 CONCLUSIONS

The main conclusions drawn up to now are summarized in the following points:

- The present methodology, developed in the framework of the SPAR-CSN project, allows to standardize the identification of DEC-A sequences in PSA level 1 models and quantify their risk by representative FoM (DEC-B_freq and $CCDP_{DEC}$).

- The application of the methodology to the SPAR-CSN model has revealed 14 DEC-A sequences (10 from the model and 4 by expert judgment) with quantitative relevance. Three sequences from this list are not included in other DEC lists of regulatory bodies.
- Different modelling hypothesis of dependencies between human actions are among the causes that result in a high relative risk of the 3 mentioned sequences ($CCDP_{DEC}$ >1.0E-02 and DEC-B_Freq >1.0E-07 1/y). These sequences are:
  1) SBLOCA consequential of an SLB with actuation of HPSIS both in injection and recirculation modes.
  2) SBLOCA consequential of an SGTR with actuation of HPSIS both in injection and recirculation modes.
  3) SBLOCA/MBLOCA with failure to cooldown and depressurize RCS and actuation of HPSIS both in injection and recirculation modes.
- As an example of Post-Fukushima improvements, the implementation of PTSSs could have a reasonable impact on level 1 PSA models, reducing the expected fuel damage frequency. Similarly, PTSSs affect the DEC-A sequences, reducing their relative risk or creating new situations with their own related risks.

Finally, it is important to mention future work will allow to analyze the impact on DEC-A sequences of other post-Fukushima improvements (Load Shedding, Portable equipment implementation, etc.), implemented in the Spanish NPPs.

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