Application of a Dynamic Event Tree Methodology to Steam Generator Tube Rupture Sequences

C. Queral, M.J. Rebollo, G. Jimenez-Varas and L. Ibáñez
Universidad Politécnica de Madrid, Madrid, Spain
cesar.queral@upm.es

J. Gil, I. Fernández, J. J. Gómez-Magán and H. Marrao
Indizen Technologies S.L.
c/ Tarragona 30, 28045 Madrid, Spain.

M. Sánchez-Perea, J. Hortal, JM. Izquierdo and E. Meléndez
Consejo de Seguridad Nuclear (CSN)
c/ Justo Dorado 11, 28040 Madrid, Spain

ABSTRACT

The Integrated Safety Assessment (ISA) methodology, developed by the Spanish Nuclear Safety Council (CSN), has been applied to a thermo-hydraulical analysis of a Westinghouse 3-loop PWR plant by means of the dynamic event trees (DET) for Steam Generator Tube Rupture (SGTR) sequences. The ISA methodology allows obtaining the SGTR Dynamic Event Tree taking into account the operator actuation times. Simulations are performed with SCAIS (Simulation Code system for Integrated Safety Assessment), which includes a dynamic coupling with MAAP thermal hydraulic code. The results show the capability of the ISA methodology and SCAIS platform to obtain the DET of complex sequences.

KEYWORDS

Integrated Safety Assessment (ISA); Dynamic Event Tree (DET).

1. INTRODUCTION

As part of the collaboration between Universidad Politécnica de Madrid (UPM), Indizen Technologies and the Spanish Nuclear Safety Council (CSN), an analysis of Steam Generator Tube Rupture (SGTR) sequences in a PWR Westinghouse has been performed with SCAIS, see [1]. The objective of the analysis has been the application of the Integrated Safety Assessment (ISA) methodology in order to obtain the SGTR Dynamic Event Tree taking into account the operator actuation times.

The ISA methodology has been developed by the Modeling and Simulation (MOSI) branch of CSN. ISA is an adequate method to perform the uncertainty analysis, especially suited to compute uncertainties for those sequences where some of the events occur at uncertain times (time delay of operator response and other stochastic events) along with usual parametric uncertainties. The numerical results of this methodology include among others of the Damage Exceedance Frequency (DEF) for the sequences stemmed from an initiating event. This is done along with the delineation of the dynamic event tree and the identification of the damage domain (DD) of the sequences that contribute to the total DEF. The damage domain is defined as the region of the space of uncertain parameters of interest that results in damage (see [2]).

DEF is then computed by integrating the general mathematical framework of ISA equations for the damage frequency (TSD, Theory of Stimulated Dynamics, see [6]). The UPM group has applied extensively this methodology in several projects; for more details see [1] to [5]. ISA methodology introduces some differences with respect the classical Probabilistic Safety Analysis (PSA):

- **Header Demand:** In PSA event trees, header intervention (i.e., demand of a safety function) is decided on the basis of generic analyses. On the contrary, demand for header intervention in ISA is a simulation result. As a result, the number of possible branches in a header is different in PSA and ISA. In PSA there are two branches for a header: failure or success, but ISA considers three possible branches for a header in every sequence: demanded with failure, demanded with success and not demanded.

- **Success Criteria:** Event tree headers in PSA are usually defined at safety function level, i.e., each header represents the successful achievement of a safety function. System success criteria are therefore needed to develop the header fault trees. In the ISA context, however, event tree headers can represent hardware states (system trains working or not) or operator actions. Therefore, ISA fault trees are used to calculate the probability of each system configuration, not to quantify failure probabilities.

- **Human Actions:** In PSA a human action is failed if it is not performed within a pre-specified time interval (available time). An action delayed beyond the available time is treated as a non-performed action. In ISA methodology, human actions are events occurring at uncertain times. A delayed action is still a performed action even if it is not able to avoid a damage condition (limit exceedance). As a consequence, a PSA success sequence, when analysed in the ISA context, may contain a non-empty damage domain resulting from excessive delays of protective actions.

- **Available Times:** In PSA the available time of a header has a value for each sequence. In ISA methodology it is a function of the uncertain times and parameters and also the status of the systems that have been demanded during the sequence.

- **End State:** The end state of a sequence in PSA event trees is a discrete variable with two possible values: either success or failure. The end state of ISA sequences, however, is a random variable where each final state (damage or success) has an associated probability. Success and failure probabilities are obtained from the sequence uncertainty analysis. PSA end states can be seen as a particular case of ISA end states where the only possible probability values are 0 or 1.

- **Failure Probabilities:** In PSA the systems failure probabilities do not depend on the dynamics of the sequence. In ISA methodology the failure rate could depend on process variables (i.e. temperature or humidity conditions in the proximity of a pump). The general mathematical framework of ISA equations for the damage frequency is the Theory of Stimulated Dynamics (TSD), see [6]. These equations are simplified if the failure rates do not depend on the process variables, as it is the case in this analysis.

- **Damage Condition:** In PSA Level 1 the damage condition is the LOCA acceptance criterion, Max PCT > 2200 F (1477.15 K). In ISA methodology several damage criteria can be handled within the same analysis, allowing obtaining the DEF for all the safety variables (safety barriers) of interest.

Application of ISA methodology can be split into the following blocks (the general block-diagram is shown in Fig. 1, see also [1]):

- **Block A**, the *sequence generation* module performing the simulation of dynamic event trees. This will provide the candidate sequences with non-trivial DD (success or damage for all conditions) that will be analyzed in detail in the Path Analysis module (Block B).

- **Block B**, the *paths analysis* module that is repeatedly simulated with different values of uncertain parameters and/or time delays (human actions or stochastic phenomena) of each sequence of interest obtained in block A. Each such simulation, called a path, can end either in a success or damage state. The region of parameter and/or time delays values that leads to damage paths is the DD of the sequence.

- **Block C**, the *probability and delay times quantification* module that provides the necessary information to calculate in Block D (Risk Assessment) the probabilities and the contribution to DEF of each sequence of interest.

- **Block D**, the *risk assessment* module that calculates the DEF by integrating on the DD region identified in block A, the probability distributions obtained in Block B (Path Analysis module).

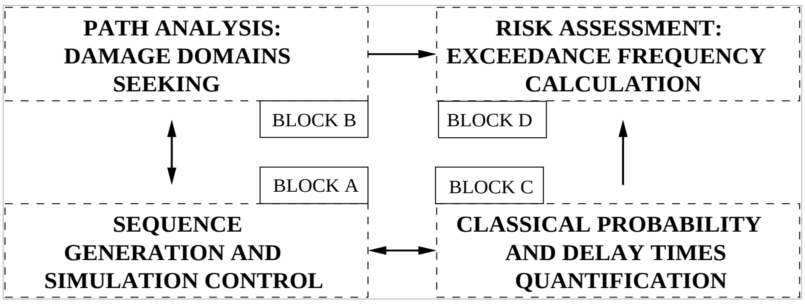

Fig. 1. ISA methodology general diagram.

Apart from a theoretical approach that is at the basis of the method, application of ISA requires a set of computational tools. A suitable software package called SCAIS (Simulation Code system for ISA) implements the above referred method, see [1]. Current SCAIS development includes as main elements:

- General Simulation Driver (BABIECA), that solves step by step topologies of block diagrams.
- Event Scheduler (DENDROS), that drives the dynamic simulation of the different incidental sequences. Its design guarantees modularity of the overall system and the parallelization of the event tree generation.
- Plant Models, allowing simulation of nuclear accident sequences. This includes codes for simulation of thermal hydraulics and severe accident phenomenology, as well as codes for simulation of operating procedures and severe accident management guidelines, for more details see [7]. Codes as MAAP, RELAP, TRACE can be adapted

to perform tree simulations under control of the scheduler. At present MAAP4, see [8], is coupled to BABIECA to build up a distributed plant simulation[1].

- Probability Calculator, which incrementally performs the Boolean product of the fault trees corresponding to each system that intervene in the sequence, additionally computing its probability.
- Path Analysis Module, which repeatedly simulates each sequence of interest with different values of uncertain parameters and/or time delays (human actions or stochastic phenomena).
- Risk Assessment Module, which calculates the DEF by integrating TSD equations on the DD region.

2. SEQUENCES GENERATION MODULE. DYNAMIC EVENT TREE SIMULATION

The objective of Block A of the ISA methodology is to simulate the dynamic event tree (DET) stemming from an initiating event. At present, the simulations of DET performed by coupling MAAP and DENDROS are performed in an automatic way, see [7].

2.1. Application to SGTR Sequences.

In this study a SGTR event at full power in a three-loop PWR Westinghouse design has been considered. Such accidents begin as a breach barrier between the primary Reactor Coolant System (RCS) and the secondary side of the steam generator (SG), and provide a direct release path for RCS fluid to the environment via the secondary side (steam-dump, safety and relief) valves.

Main human actions within Emergency Operating Procedures (EOP) needed in order to optimally recover the transient are depicted in Fig. 2. With these actions in mind, the principal stages of SGTR sequences are:

- ***Reactor trip and Safety Injection (SI) signal.***
  Due to SGTR the reactor coolant inventory decreases and leads to a manual/automatic reactor trip. The decrease in RCS pressure results in a low pressurizer pressure SI signal, Main Feed Water (MFW) system trip and actuation of the Auxiliary Feed Water (AFW) system to deliver flow to all steam generators.

- ***Identification and Isolation of the ruptured SG.***
  Once the ruptured SG has been identified, recovery actions begin by Isolating AFW flow to the ruptured SG and closing the Main Steam Isolation Valve (MSIV) on the steamline corresponding to the affected SG, aiming to minimize radiological releases, to reduce the possibility of overfilling the affected SG and to enable the operator to establish a pressure differential between the ruptured and intact SGs as a necessary step toward terminating primary to secondary leakage.

- ***Cooldown of the RCS system by means of the intact SGs.***
  After isolation of the ruptured SG, the RCS is cooled as fast as allowed, dumping steam from the intact SGs. In the case of unavailability of the normal steam dump system to the condenser; this cooldown is performed by dumping steam via the Power Operated Relief Valves (PORVs) on the intact SGs. The cooldown is finished when the cooldown target temperature is reached.

[1] Currently, a coupling to TRACE similar to the case of MAAP is being developed by Indizen in collaboration with CSN, see [7].

- ***Depressurization of RCS to restore inventory.***
  During the cooldown process, SI flow will tend to keep RCS pressure and primary to secondary break flow will continue. Consequently, SI flow must be terminated to stop break flow; however, adequate inventory must be first assured. This includes both sufficient RCS subcooling and pressurizer inventory to maintain a reliable pressurizer level indicator after SI flow is stopped. The depressurization is performed using normal pressurizer spray or a pressurizer PORV.

- ***Terminate SI.***
  Once RCS subcooling, secondary side heat sink, and reactor coolant inventory have been adequately established, SI flow is no longer required. Thus, SI flow is stopped to terminate primary to secondary break flow and to prevent repressurization of the RCS.

- ***Long term cooling.***
  Finally, RHR system provides with long term cooling.

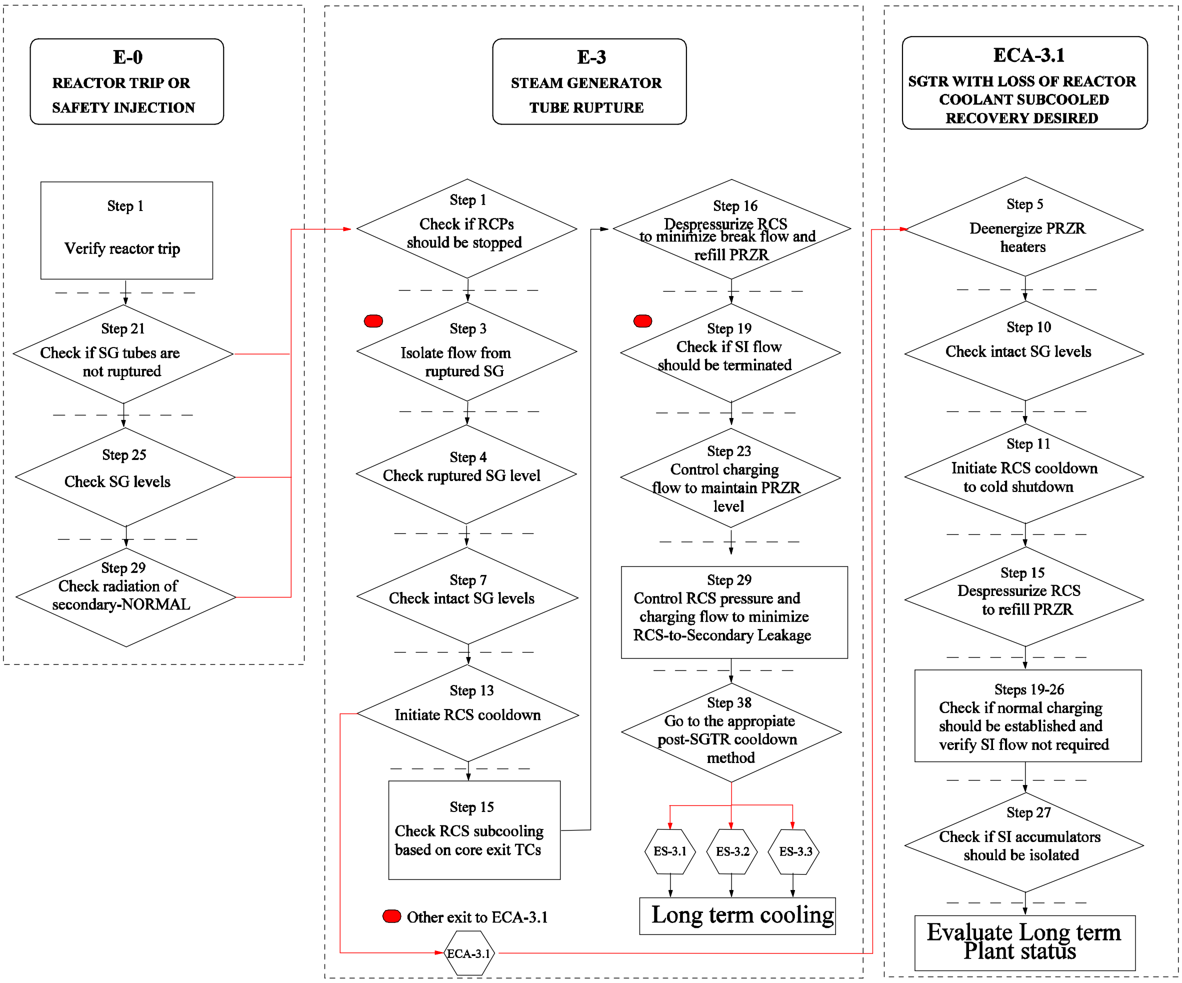

Fig. 2. Summary of standard Westinghouse EOPs in the case of SGTR sequences.

In a first step, several SGTR event trees (ET), corresponding to PSA studies of similar nuclear power plants (Westinghouse design with 3 loops) have been analyzed to build a generic SGTR event tree including EOPs, Fig. 3. Sequence headers and success criteria considered after this review are:

SCRAM: Reactor trip; **HPI:** High Pressure Injection system (1/2 pumps); **AFW**: Auxiliary Feed Water system (1/3 pumps); **ISO-SG:** Isolate ruptured SG (close MSIV on ruptured SG);

DSP-EP: Cooldown and Depressurization of RCS (cooldown dumping steam from PORVs on intact SGs and depressurization with pressurizer PORV); **DSP-LP**: Cooldown and depressurization of RCS (cooldown, 55 K/h rate, dumping steam from PORVs on intact SGs and depressurization with pressurizer sprays; **FB**: Feed and Bleed (1/2 HPI pumps, 1 PORV); **C-PORV/RSIS:** Terminate SI (control charging flow); **REC-HP:** High Pressure Recirculation (injection to 2/3 legs of RCS with 1/2 HPSI pumps and 1/2 LPSI pumps); **RWST:** Refill of Water Storage Tank; **RHR**: Residual Heat Removal.

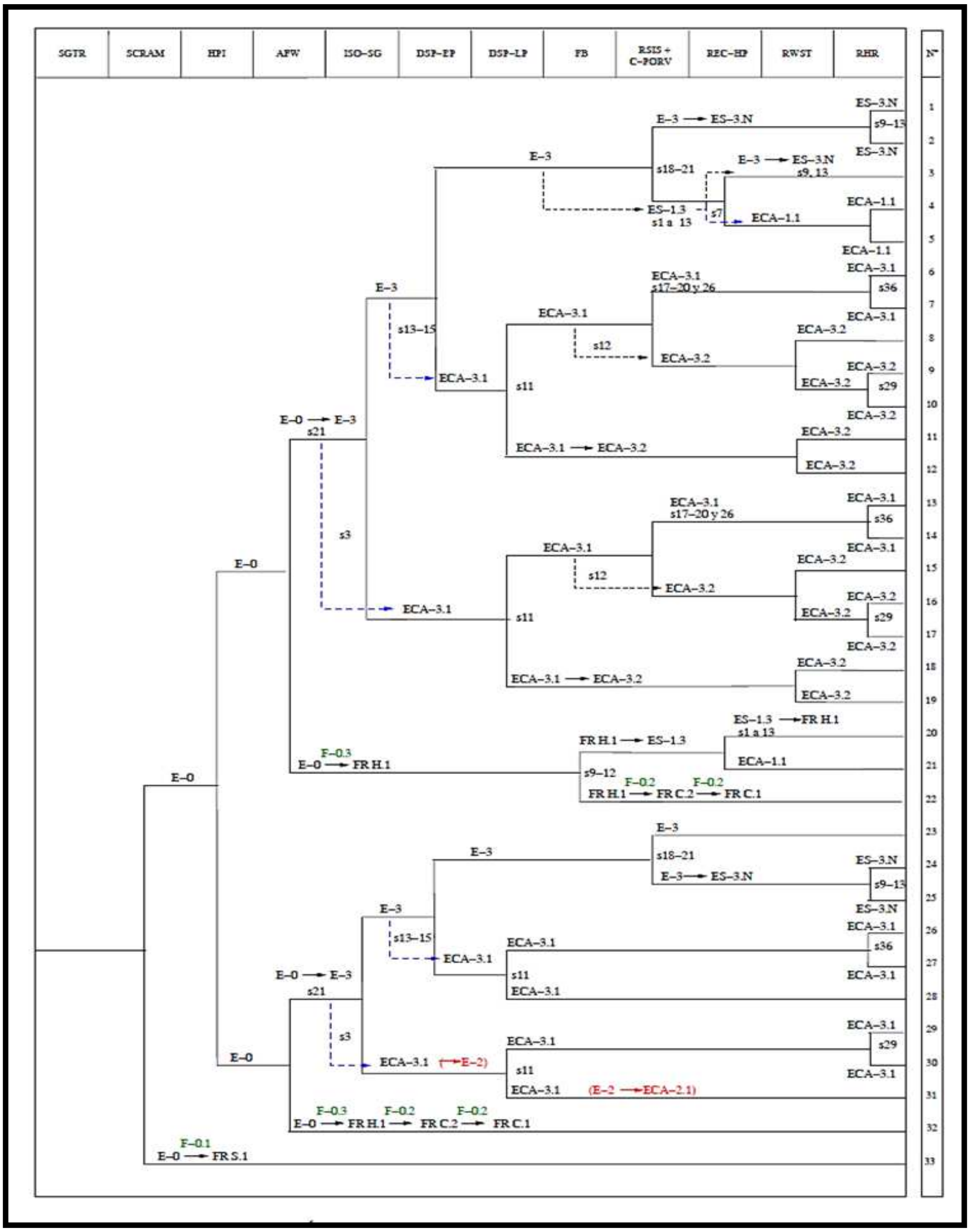

Fig. 3. SGTR. Generic Event Tree (GET) with EOPs.

One of the main difficulties in SGTR simulations is the selection of the operator action timing, which is very plant-specific. Nevertheless the timing are in the same range comparing similar plants based on operator training on full-scope simulators, see Table 1 and see also [9] to [16].

Taking into account this information, a set of representative values for the DET-SGTR analysis has been obtained, see Table 2. The total time required to complete the recovery operations lies of both operator action time and system plant response times. For instance, the time for each of the major recovery operations (i.e., RCS cooldown) is primarily due to the time required for the system response, whereas the operation action time is reflected by the time required for the operator to perform the intermediate action steps.

Table 1. Spectrum of operator times in SGTR sequences.

Plant	WCAP-10698	Watts Bar	Beaver Valley	Harris NP	Prairie Island	Turkey Point
Reference	1987 LEWIS	1992 BOCHMAN	2006 FENOC	2000 WEC	2011 SCHIMMEL-3	2011 KILEY
Operator Action	Time (s)	Time (s)	Time (s)	Time (s)	Time (s)	Time (s)
Identify and Isolate Ruptured SG	600	900	900	720	Calculated by TH code	1200
Begin RCS Cooldown	(420-480)	429	144	300	1140 from SCRAM	1680 from SCRAM
End RCS Cooldown	Calculated by TH code					
Begin Depress.	(360-480)	147	240	240	420	360
End Depress.	Calculated by TH code					
Begin SI Termination	420	244.2	180	180	120	120
SI Termination and Pressure Equal.	Calculated by TH code					

Table 2. Summarized operator times included in DET simulation.

Operator Action	Description (EOP, step)	Time (s)
Ruptured SG Isolation	AFW flow to ruptured SG and MSIV on ruptured SG. **(E-3, step 3)**	900
Start RCS Cooldown	With PORVs on the intact SGs. **(E-3, step 13) / (ECA-3.1, step 11)**	1140 / 2260
End RCS Cooldown	Target RCS temperature	Calculated by MAAP
Start Depressurization	With PZR- PORV. **(E-3, step 16).** With PZR-spray. **(ECA-3.1, step 15).**	1780/2260
End Depressurization	RCS pressure equal to ruptured SG.	Calculated by MAAP
Terminate SI	**(E-3, step 17) / (ECA-3.1, step 19)**	2200 / 2900
Heaters control and Accums. isolation	**(ES-3.1, step 1)/(ECA-3.1, step 19)**	2900 / 3000
Start Cooldown	With PORVs on intact SGs **(ES-3.1, step 5)**	3000
Start RCS Depressurization	With PZR-spray. **(ES-3.1, step 8)**	3600
RHR	RHR conditions.	Calculated by MAAP

All simulations performed in this analysis with DENDROS-MAAP include as hypothesis Success criteria for headers **SCRAM**, **AFW** and **RC-HP;** in addition **RWST** and **RHR** headers are not included in the analysis. Therefore, the headers considered in simulations are: **HPI** (named H in DET), **ISO-SG (**named I in the DET**), DSP-EP** (named SD in DET)**, DSP-LP** (named LD in DET), **C-PORV/RSIS** (named R in DET). Simulations are finished when

RHR conditions are reached (success sequence), PCT> 1477.15 K (damage sequence) or Time > 24 hours. In addition, twenty four operator actions, corresponding to EOPs E-3, ES-3.1, ECA-3.1 and ECA-3.2, have been included in DET simulation.

The DET, Fig. 4, provides the actuation time for systems and branching time for headers. The main variables of the sequences of DET are shown in Fig. 5 to 6. For the purpose of DET unfolding, simulations do not consider time delays: each header occurs at the stimulus time or never. The identification of each sequence is carried out by the concatenation of header status: a header in upper case means success upon demand and lower case means failed upon demand. Main values of variables and times of events obtained from the sequences of DET are shown in Table 3.

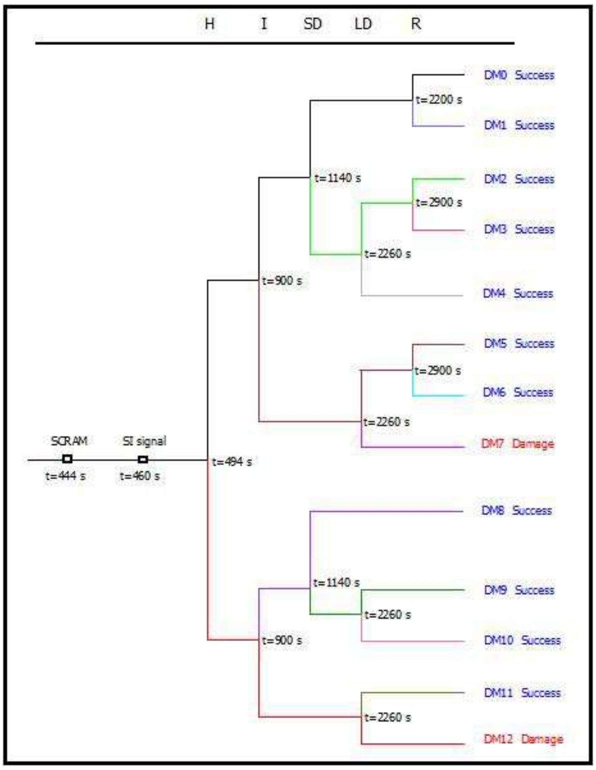

Fig. 4. SGTR. Dynamic Event Tree (DET).

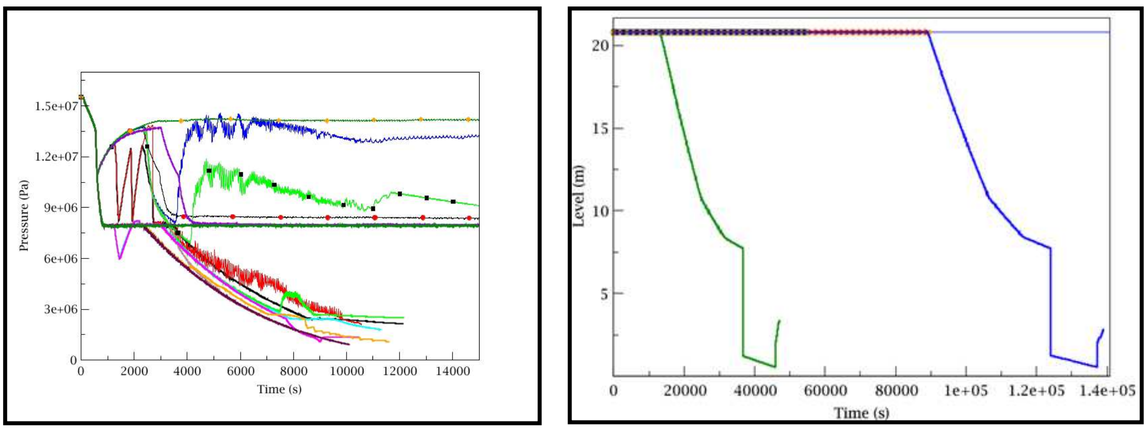

Fig. 5. RCS pressure and level for every sequence of the DET.

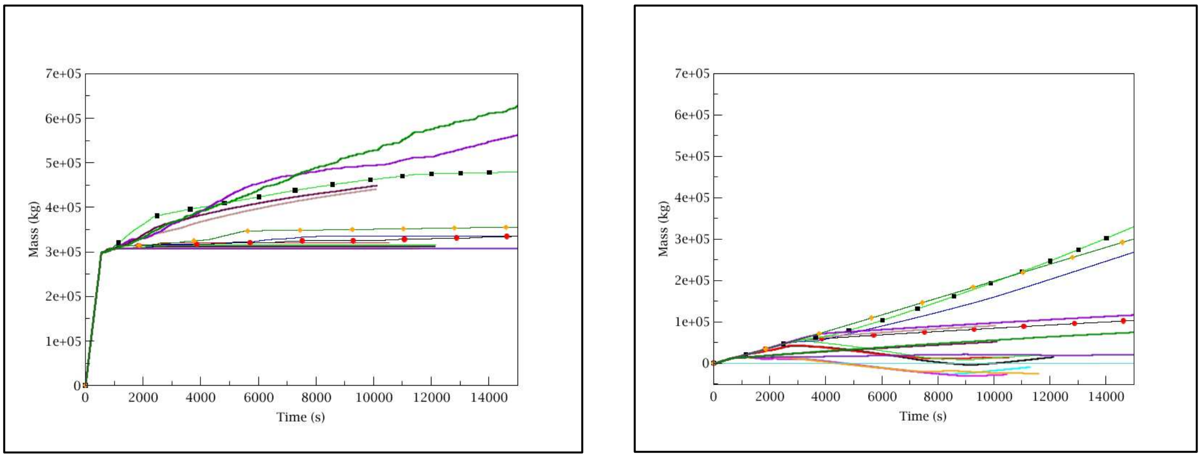

Fig. 6. Integrated mass flow rate in tube rupture and steam releases from affected SG. (Display simulation time 15.000s)

Table 3. Sequence information obtained from the reference DET.

Sequence	RCS Press. Min. (Pa)	RCS Level Min. (m)	Intg. Mass Flow break (kg)	End Release Time (s)	Total Mass Steam Release (kg)	Max. PCT (K) [Time (s)]	ACCs Injec. Time (s)	RHR Time (s)	End RWST Time (s)
DM0: H-I-SD-R	2.1E6	20.8	4.1E4	2378	3.1E5	603	-----	12053	-----
DM1: H-I-SD-r	2.1E6	20.8	4.3E4	2670	3.2E5	603	-----	----	-----
DM2: H-I-sd-LD-R	2.5E6	20.8	5.0E4	2803	3.1E5	603	-----	12067	-----
DM3: H-I-sd-LD-r	6.7E6	20.8	1.4E5	9134	3.3E5	603	-----	----	67509
DM4: H-I-sd-ld	7.8E6	20.8	1.5E6	76811	4.0E5	603	-----	----	74264
DM5: H-i-LD-R	9.1E5	20.8	9.1E4	9981	4.4E5	603	-----	9981	-----
DM6: H-i-LD-r	2.5E6	20.8	1.4E6	54576	5.1E5	603	-----	----	53111
DM7: H-i-ld	7.4E6	0.57	1.6E6	-----	1.9E6	>1500 [137000 s]	-----	-----	73215
DM8: h-I-SD	1.1E6	20.8	1.4E4	949	3.1E5	603	-----	10380	-----
DM9: h-I-sd-LD	1.1E6	20.8	1.3E4	847	3.1E5	603	5151	11513	-----
DM10: h-I-sd-ld	7.8E6	20.8	1.3E4	847	3.1E5	603	-----	----	-----
DM11: h-i-LD	9.1E5	20.8	5.2E4	-----	4.5E5	603	-----	10017	-----
DM12: h-i-ld	6.9E6	0.57	1.5E5	-----	1.4E6	>1500 [46823 s]	47023	----	-----

Results of DET show that damage end status is reached for sequences DM7 and DM12 (Fig. 3) which corresponds to sequences S19 and S31 in GET, (Fig. 2). However in the GET there is another damage sequence (S12) which corresponds to one success sequence DM4, in DET.

3. FUTURE WORKS: PATH ANALYSIS AND RISK ASSESSMENT.

The Path Analysis Module (Block B) receives the sequence and parameter information of all branches of DET from the Sequence Generation Module (Block A) and determines the DD of the candidate sequences. At present, the simulations performed by coupling MAAP and PATH-ANALYSIS are performed in an automatic way.

Headers that may occur at uncertain times (mainly operator actions but also events with stochastic phenomenology) are defined as Non Deterministic Headers (NDH). In order to take into account this uncertainty a time sampling between the minimum time when the header event becomes possible and a maximum time (or the mission time, 24 hours) is performed for each NDH, see Figure 7. The approach for obtaining the DD of a sequence is shown in Fig. 8. If there are several non-deterministic headers and/or uncertain parameters, a multidimensional time/parameter sampling will be needed. Each sample gives rise to a path belonging to the sequence and the set of paths leading to a damage condition (i.e., exceedance limit) that depicts the DD of the sequence.

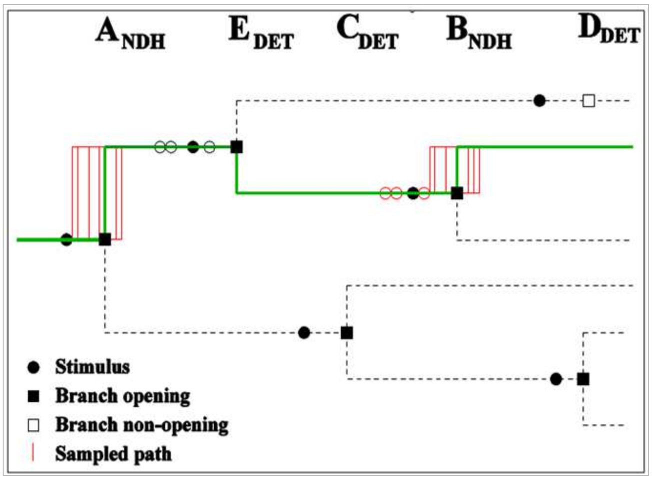

Fig. 7. Path analysis in a sequence with two NDH (headers A and B).

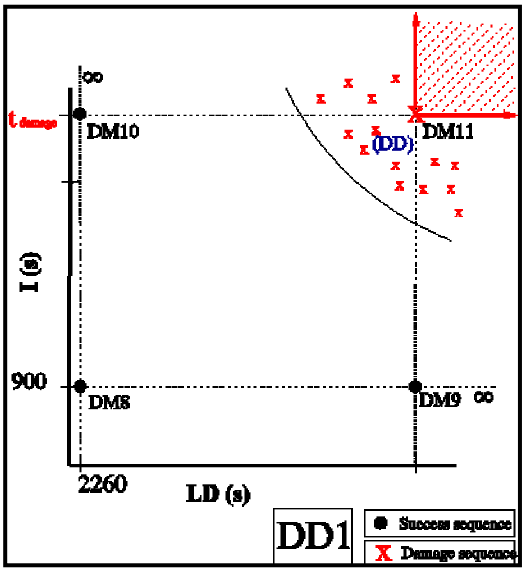

Fig. 8. Examples of Damage Domain (DD).

Once the DD is obtained, then it is possible to calculate the DEF by integrating the TSD equations inside the DD of each sequence ([6]). This integration module constitutes the Risk Assessment module (Block D, see Fig. 1). TSD equations evaluate the frequency density of each path within a sequence, and need several probabilistic data that can be obtained from several sources like pre-existing PSA's and stochastic phenomena models (Block C, see Fig. 1). TSD framework uses the concept of "stimulus" of a dynamic event header, defined as a condition that enables the event. For instance, in the case of a protective action the stimulus is the demand of that action, directly derived from the simulation results. In addition, the probability distributions of NDH do not show mutual dependencies and do not depend on physical variables, i.e., probability distributions are known functions of the delay from the activation of the stimulus to the actual occurrence of the event.

Path analysis and Risk Assessment (Blocks B and D of ISA methodology, see Fig. 2) have not been applied to this SGTR analysis, a research that will be performed in a next future. However, they have been included in other sequence analyses like Loss of Coolant Accident and Loss of Component Cooling Water System in PWR. Further details can be found in [2], [3], [4], [5].

4. CONCLUSIONS

The results of DET simulation have shown that GET damage sequences are adequately reproduced by DET simulation; with the exception of one GET damage sequence which is found to be a success sequence in DET. This result shows the capability of DET analysis in order to perform PSA verification.

In addition, it is known that in PSA each sequence has a well-defined final state, success or damage. This analysis has pointed out that depending on operator action times, it is possible to have a candidate sequence for the DD, sequence with damage probability and a success probability, illustrating the importance of Path Analysis and Risk Assessment.

This paper shows an application of the ISA methodology for the analysis of SGTR sequences using MAAP-SCAIS codes. In general, the results have shown the capability and necessity of an ISA-like methodology in order to properly account for uncertainties in the time delay of operator response and other stochastic events along with usual parametric uncertainties in the evaluation of the safety in a NPP.

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