

DYNAMIC EVENT TREE ANALYSIS AS A TOOL FOR RISK ASSESSMENT IN NUCLEAR FUSION PLANTS USING RAVEN AND MELCOR *

M. D'Onorio[‡], T. Glingler, F. Giannetti, G. Caruso

Sapienza University of Rome, Department of Astronautical, Electrical and Energy Engineering (DIAEE)– Nuclear Section

Corso Vittorio Emanuele II 244, 00186 Roma, Italy

Abstract

In the broad framework of the nuclear power plants industry, the dynamic probabilistic risk assessment could answer the time dependence deficiency of the event tree and fault tree analysis. The basic event tree approach relies on experts' pre-constructed accident sequences without exploring the time-dependent nature of an accident scenario, which could strongly affect the accident sequence. Conversely, effects of events timing can be studied adopting a Dynamic Event Tree (DET) approach.

Developing a DET methodology requires integrating a system code capable of replicating an accident scenario and a logic-driver code able to generate the event tree sequence, trigger plant safety systems, and manage other relevant events throughout the simulation. For this purpose, MELCOR and RAVEN have been coupled through a Python script developed by the Sapienza University of Rome to perform dynamic event tree studies during accident transients in fusion and fission reactors.

RAVEN is a software tool developed at the Idaho National Laboratory (INL) to act as a control logic driver and post-processing tool for different applications. MELCOR for fusion is a fully integrated design basis and severe accident code that simulates thermal-hydraulic behavior and self-consistently accounting for aerosol transport in nuclear facilities and reactor cooling systems for the evaluation of the source term in fusion reactors.

The coupling between these codes will provide a wide range of NPP risk assessment analyses, establishing new best practices.

In this work, a preliminary dynamic event tree study has been performed, selecting as initiating event an ex-vessel LOCA in the WCLL Test Blanket System to be tested in ITER. Time-dependent parameters such as the intervention of the plasma shutdown system and the closure of the main system isolation valves have been sampled to study evolving system scenarios.

I. INTRODUCTION

Recent years have shown an increasing interest in Probabilistic Risk Analysis (PRA) as a primary tool to

analyze the safety and reliability of complex engineered systems such as nuclear power plants [1]. The PRA methodologies need to satisfy a high level of quality assurance to comply with nuclear power plants increasingly strict safety requirements. Standard PRAs techniques quantify the probability of a pre-constructed event based on expert judgment using a conservative approach. Thus, they could underestimate possible scenarios by not considering the time dependence of certain events. Describing a complex accident scenario with a predefined set of scheduled events is a source of error since potentially dangerous scenarios are missed or underestimated.

Each event could have a huge difference, whether it happens at a specific time frame or another, leading to different results. Moreover, solving the dynamic nature of an accident sequence also includes the interactions between different events such as plant control logic interventions, stochastic failures of equipment, and human operator actions.

Therefore, standard PRA techniques cannot catch the intrinsic dynamicity of an evolving accident scenario since the "time" variable is not accounted [2][3].

The accidents in a tokamak-type reactor are characterized by phenomena in which the temporal dependence of the accident sequence can lead to profoundly different results. Two fundamental aspects become effective while exploring the accidental scenario that highlights the criticalities of a process: the chain of events and the time at which they occur.

The Dynamic Probabilistic Risk Analysis (DPRA) approach solves this fundamental lack of standard PRA methodologies, ensuring improved outstanding quality and accuracy.

A dynamic event tree analysis has been performed for an ex-vessel Loss Of Coolant Accident (LOCA) occurring in the main loop of the ITER Water Cooled Lithium Lead Test Blanket System (WCLL TBS) [4]. This test-case analysis has been focused on investigating the plasma ramp-down and the SIC-2 triggering time. The present work will demonstrate the capabilities of a DPRA analysis obtained by developing an interface to use the RAVEN DET capabilities with the MELCOR severe accident code.

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[‡] email: matteo.donorio@uniroma1.it

II. THE DYNAMIC PRA

DPRA improves the standard PRA by introducing time as a main parameter. The emergency systems intervention time affects the success or failure of mitigating the risks of an accident sequence. Therefore, a complete and exhaustive risk analysis must account for the chance of emergency systems to intervene at different time frames during an accident sequence or possibly fail in their operation. The DPRA methodology can answer these specific and other needs.

As explained in [5], DPRA could be achieved by integrating simulation codes (e.g., RELAP-5, MELCOR, MOOSE, MAAP) with sampling and control tools (e.g., RAVEN) [6][7][8]. Initial conditions of the simulation run could be several variables X_r ($r = 1, \dots, R$) sampled from their specific distribution and set as simulation boundary conditions. The simulation is based on two different types of variables:

- $s=s(t)$: describes the status of the component/system during each time frame of the simulation;
- $m=m(t)$: represents the physics-based temporal evolution of a simulated accident scenario (temperature or pressure in a specific system node).

Each simulation run can be represented as a trajectory in the phase space where the evolution is described as follows:

$$\begin{cases} \frac{\delta s}{\delta t} = \Gamma(m, s, t, X_1, \dots, X_R) \\ \frac{\delta m}{\delta t} = \Xi(m, s, t, X_1, \dots, X_R) \end{cases}$$

Equation 1. Phase space evolution of thermodynamic parameters (m) and component status (s) [5]

where Ξ is the actual simulator model that describes how m evolves in time (e.g., MELCOR), and Γ is the operator that describes how s evolves in time, i.e., the status of components and systems at each time step (system control logic) [5]. The sequence starts by sampling a value for each chosen variable X_r from its corresponding Probability Distribution Function (PDF) in the DET simulation. As the simulation proceeds, a selected number of branching conditions could be satisfied if a corresponding sampled variable meets some imposed conditions (e.g., a pressure overcomes a sampled setpoint value).

In general, DET methodologies are adopted to take the timing of events as a central variable to understand how the system could react in the different circumstances and becomes particularly relevant when uncertainties in complex phenomena are considered.

The main idea is to let a system code explore an accident sequence within a probabilistic environment. A

visualization of the DET development is shown in Figure 1.

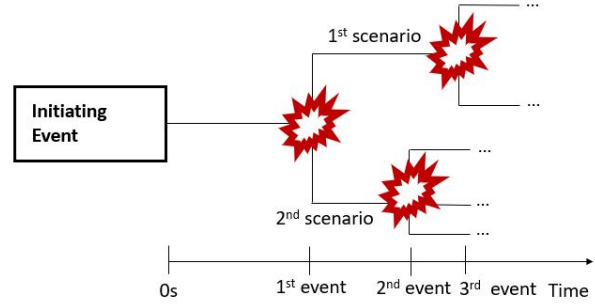


Figure 1. Visualization scheme of a DET simulation

III. RAVEN AND MELCOR COUPLING FOR DET STUDIES

MELCOR [9] is a fully integrated severe accident code that simulates the thermal-hydraulic phenomena in steady and transient conditions. It has been developed at Sandia Laboratories for the U.S. Nuclear Regulatory Commission as a tool for evaluating second-generation plants PRA. The Idaho National Laboratory (INL), among the Fusion Safety Program (FSP), made fusion specific modifications to the MELCOR v. 1.8.6 code [10]. These modifications allowed MELCOR to assess the thermal-hydraulic response fusion reactor cooling systems and the transport of tritiated water during accident conditions.

Developed at INL, RAVEN (Reactor Analysis and Virtual control Environment) is a software framework able to perform parametric and stochastic analysis based on the response of complex system codes and provide a helpful tool to perform risk analysis [11] [12]. Initially developed to provide dynamic risk analysis coupled with RELAP-7, now the code is fully mature and acts as a multi-purpose stochastic and uncertainty quantification platform.

RAVEN capability to be coupled with other system codes simplified the Python development of the current DET interface. Moreover, a RAVEN-MELCOR coupling script was developed by the Sapienza University of Rome DIAEE department to perform sensitivity and uncertainty studies [13][14][15]. This already developed interface has been recently improved and extended to carry out dynamic probabilistic risk studies with MELCOR.

The DET analysis starts with a sampling strategy of selected variables of interest. The first step of the algorithm is to overwrite the sampled values in the MELCOR input deck, in particular the so-called Trip Variable (TV). A TV is a logical Control Function (CF) representing a particular event in the accident sequence. For example, it could be represented by the area of a broken pipe in a LOCA accident or by the pressure limit of a tube in a Loss Of Flow Accident (LOFA) scenario. Those variables are scripted in the MELCOR input deck and constitute the "trip variables" group. Each time a TV changes its logical state from FALSE to TRUE, the

MELCOR simulation stops. At this point, RAVEN detects the TV name and the time frame at which the calculation of the MELCOR run stopped. Afterward, the DET tool creates two branches, one for the "happened" event and the other as if the event did not happen. The script must change the MELCOR input for each branch to restart the simulation and sample (if necessary) a new value.

Unfortunately, MELCOR v.1.8.6 for fusion applications does not allow changing the CF status (TRUE or FALSE) in the MELCOR input deck before the restart.

The status of trip variables is defined using the MELCOR External Data File (EDF) package to overcome this issue. The EDF package offers the possibility to pass data to MELCOR using external text files containing data grouped in columns. For each DET simulation, the developed Python script automatically writes EDFs containing the time the simulation stops, a constant (e.g., 0 or 1) used for the different branching conditions, and the RAVEN sampled variable. The DET simulation continues until another logical TV changes its state. For each branch, the conditional probability is calculated.

The outcomes of a DET analysis could be numerous, from revealing critical edge scenarios to calculating source terms at the end of a specific branch. It is up to the user to structure the initial input accurately to achieve the required results. Figure 2 summarizes the different steps of the DET algorithm used in MELCOR for fusion applications.

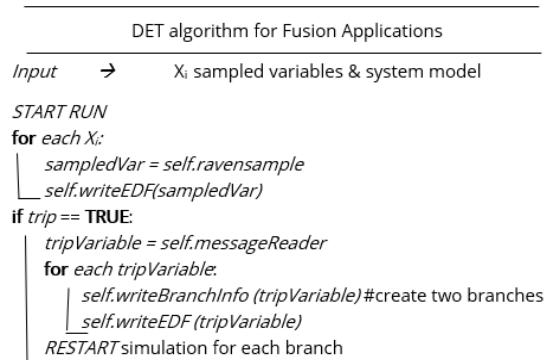


Figure 2. DET algorithm for fusion applications

IV. TEST CASE: EX-VESSEL LOCA FOR ITER WCLL TBS

The case study selected to show the capabilities of the developed DET tool is a LOCA accident scenario for the ITER WCLL TBS. The Postulated Initiating Event (PIE) is a Double Ended Guillotine Break (DEGB) of the 3" TBM inlet Water Cooling System (WCS) pipe during a plasma burn phase with resulting loss of water into the port cell. The break has been located on the TBM-set inlet line upstream SIC-1 safety isolation valves to maximize the potential coolant loss.

The MELCOR model of the WCLL TBS has been developed in the framework of Safety And Environment

(SAE) work package of the H2020 EUROfusion project to support its design and integration into ITER [16]. The model includes a detailed representation of the TBM box, WCS, Tokamak Building, and Port Plug frame. The MELCOR input deck and the nodalization scheme of the TBM set have been developed following the fusion breeding blanket accident analysis methodology reported in [16]. A scheme of the WCS system nodalization implemented in MELCOR is shown in Figure 3. While, an overview of the nodalization scheme adopted for the TBM-set is depicted in Figure 4. All the details concerning the MELCOR model can be found in reference [17].

The PIE occurs during a ITER pulsed plasma regime. The plasma pulse pattern foresees the full plasma power to be reached within 60 s and, after 450 s of flat-top, the power is ramped down in 200 s (see Figure 5). The dwell time between two consecutive plasma pulses is 1090 s. The implemented system logic and the safety systems determine how the accident develops in terms of released inventories to the containment and accident evolution with related consequences. The inventory released could depend on the WCS isolation logic driven by the closure settings of the SIC-1 and SIC-2 valves. The time needed to fully close the SIC-2 valves has been assumed to be 3s. The plasma shutdown can occur, during normal operation, after 200 s by a pulse sequence ending. It can also be forced by activating the Fusion Power Termination System (FPTS) (order of 3 s not assessed in this work).

The FPTS produces a disruption with a relatively higher thermal load on plasma-facing components, possibly determining First Wall (FW) failure. Thus, if the accident sequence is not appropriately mitigated, a beyond design basis accident could occur, evolving the ex-vessel LOCA into an in-vessel LOCA.

V. DET SAMPLING STRATEGY

The DET analysis could add more investigating goals to classical simulations. For this purpose, two parameters have been selected to test MELCOR DET capabilities. These two parameters are:

- The triggering time of the plasma ramp-down procedure after the LOCA;
- The triggering time for SIC-2 valve closure after the LOCA.

A uniform distribution has been assigned to each variable. The sampling upper and lower limits have been set to 3 s and 51 s after the PIE rupture event for the plasma ramp down triggering time, and for the SIC-2 triggering time the upper and lower limit has been set between 7 s to 55 s. For each variable, 17 equally distanced values are sampled to generate 289 final branches of the DET simulation.

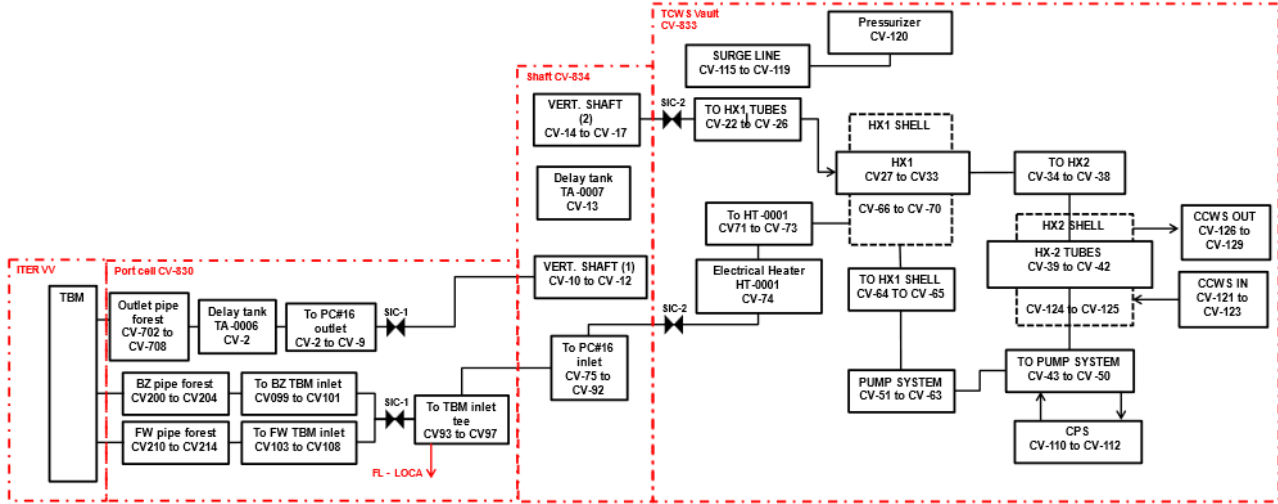


Figure 3. The MELCOR WCS model nodalisation scheme [15]

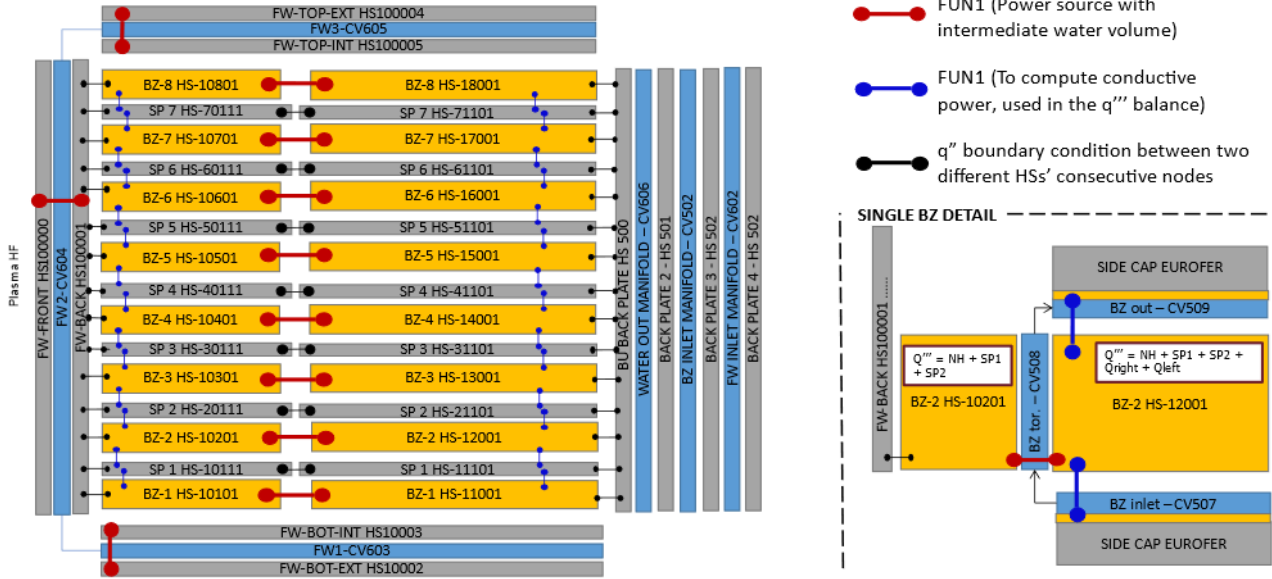


Figure 4. WCLL TBM control volumes and heat structure nodalisation [15]

The sampled parameters have been chosen to investigate their influence on FW temperature transient and Tritiated Water (HTO) released from the coolant system.

A logic CF is used for each branching condition. When the CF changes its value from FALSE to TRUE, the MELCOR simulation stops, and two branches are created for the next run simulation exploring a different sampled value.

Figure 5 shows the plasma pulse pattern and the fixed time instant of the PIE event occurring at 100 s. For the fixed PIE event, the DET simulation explores sequential intervention time frames, through a sampling procedure of the above-cited safety procedures. Each couple of sampled values forms a complete accident scenario and relevant accidental sequence variables are analyzed and discussed in section VI.

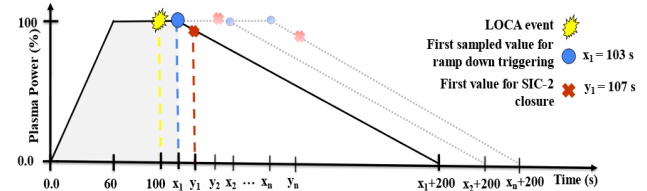


Figure 5. Example of the sampling strategy adopted for the analysis

VI. MAIN OUTCOMES

The methodology was successfully tested. The script automatically generated the DET structure following the sampling strategy defined inside RAVEN. After the LOCA event, a new branch is generated as soon as the first trip conditions defined inside the MELCOR input

deck are reached. At this point, a new run starts with a new sampled value for the variable that previously stopped the simulation. At the end of the process, 289 simulation branches are generated from a single initial MELCOR run. Each of these simulations successfully reached the imposed exit condition at 1000 s, except for one that experienced a numerical crash. In Figure 6, a simplified tree structure developed by the simulation process is shown.

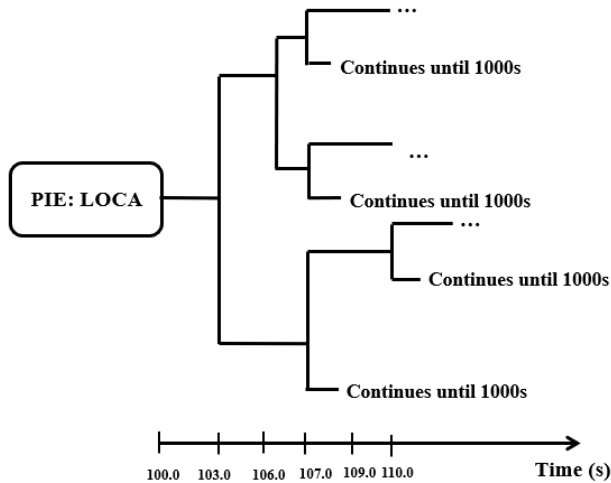


Figure 6. DET structure

The initiating event is fixed at 100 s of simulation time. The first part of the accident transient is a blowdown of the pressurized water circuit into the corresponding ITER port cell resulting in a pressure rise. A pressure relief valve is activated, releasing the steam to the cooling system room through the service shaft. Therefore, the tritiated water inside the WCS circuit is released into the PC and cooling system rooms. The analysis results focused on two figures of merit: the amount of HTO released and FW temperature.

Figure 7 shows the amount of HTO released from the WCS for the different explored scenarios. The diverse transients are correlated to the amount of HTO inventory that could be released from the rupture. This amount is strongly affected by the timing of the SIC-2 valve closure procedure.

The DET highlighted that the amount of HTO released is not affected by the timing of ramp-down procedure but depends only on the SIC-2 valve closure. Indeed, the total amount of HTO released for subsequent SIC-2 closure timings is shown in Figure 8, where only 17 different values of HTO mass can be seen. These correspond to the 17 sampled values for the SIC-2 variable. The combinations of the different simulation are overlapped on the corresponding SIC-2 sampled value. The anticipated closure of the two SIC-2 valves placed at the inlet and outlet of the TCWS vault (see Figure 3) reduces the inventory released from the WCS. However, as a countereffect, this procedure decrease the water reverse

flow from the pressurizer to the FW channels. This reverse water flow cools down the TBM structures during the accident sequence first phase (~50 s). As highlighted in Figure 7, the maximum amount of HTO released is 0.25g and corresponds to a SIC-2 valve closure of 55 s after the PIE. In contrast, the least amount of HTO released is 0.13 g, corresponding to a SIC-2 valve closure of 7 s after the PIE.

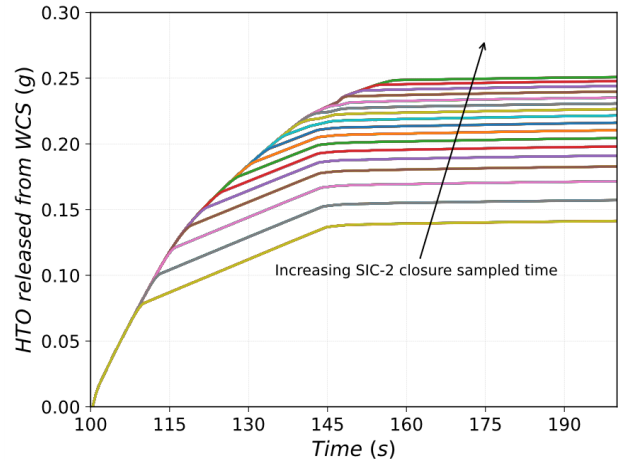


Figure 7. Amount of HTO released from the WCS

As shown in Figure 7 and Figure 8, the amount of HTO released reaches a maximum value if the closure procedure time is higher than ~60 s from the LOCA event. The final value coincides with the amount of HTO in the WCS circuit. Therefore, for SIC-2 closure timings higher than ~60 s all the HTO present in the WCS is released in the PC. For timings less than 60 s, there is no linear correlation between the SIC-2 and the amount of HTO released because of the choked flow.

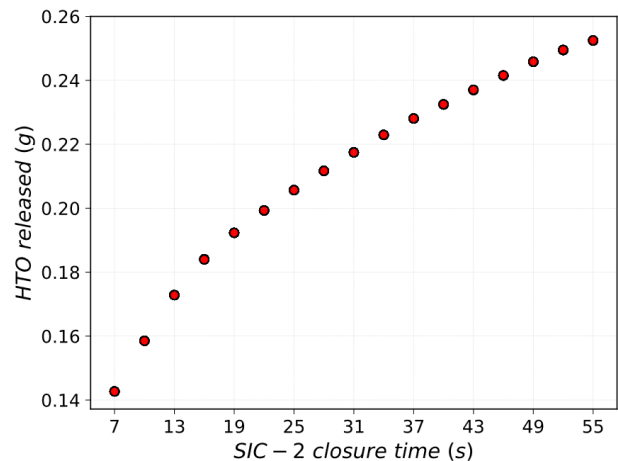


Figure 8. Total amount of HTO released associated to the corresponding SIC-2 closure time

Regarding the amount of HTO released, the best procedure corresponds to the SIC-2 closure shortly after the PIE. This result must be compared to the influence of

the SIC-2 anticipated closure on the maximum temperature reached by the FW, described in the following paragraph.

Figure 9 shows the FW temperature transients for all the different scenarios explored in the DET simulation. Both RD and SIC-2 variable timings influence the maximum temperature reached by FW during the LOCA transient. Timings of the RD procedure further from the LOCA event increase the maximum temperature reached by the FW. The RD procedure takes 200 s to reach the complete plasma termination. Therefore, during the first phases of the RD the reverse flow of the WCS inventory provides coolant to the FW channels. Soon after the coolant beneficial effect, the coolant in the FW decreases, and as shown in Figure 9 the temperature transients of the FW reach high temperatures.

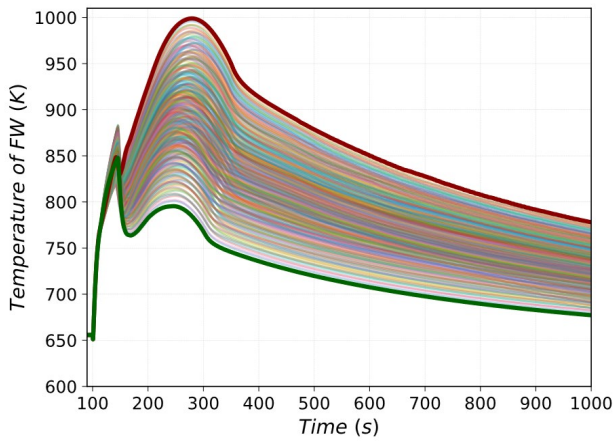


Figure 9. FW Temperature transients

In Figure 10 and Figure 11, the influence of the two sampled parameters on the maximum temperature reached by the TBM FW is reported. As already stated, a more distant closure of the SIC-2 valve permits a higher amount of coolant from the WCS inventory to the FW structure, having beneficial effects on the maximum temperature reached. Although for RD times higher than 33 s, this beneficial effect is not seen, and the maximum temperature increases. As shown in Figure 10, after 33 s of RD time, higher SIC-2 valve closure timings correspond to higher temperatures. Therefore, the amount of inventory that flows to the FW drastically reduces, not helping the FW cooling anymore.

In Figure 11, we can see the influence of the SIC-2 closure procedure in more detail. The FW maximum temperature decreases from the first value sampled of 7 s to 25 s with a constant RD time value. This trend reverses after 25 s and for higher SIC-2 valve closure timing. In conclusion, the SIC-2 valve closure procedure finds its best timing during the first phases of the accident sequence. More in detail, as shown in Figure 10, the best timing is shortly after the PIE, while in Figure 11, delaying the closure of the valve is beneficial to the FW temperature transient until the value of 25 s. The RD

procedure timing brings advantages to the FW temperature with values as close as possible to the PIE.

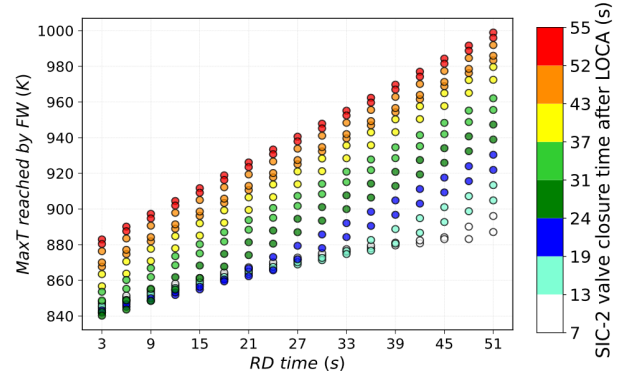


Figure 10. Max T reached by FW influenced by the two sampled values with insight on RD time

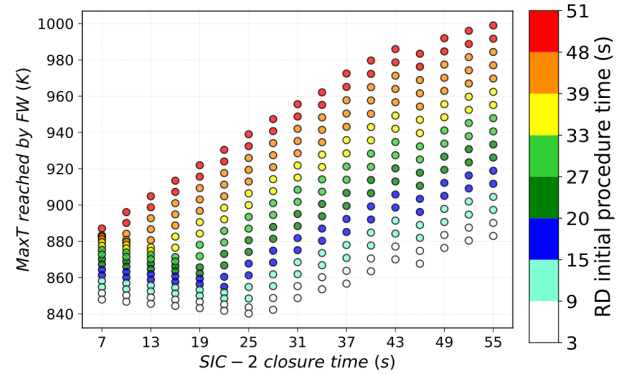


Figure 11. Max T reached by FW influenced by the two sampled values with insight on SIC-2 closure time

The optimized interval found for the sampled parameters is:

- RD time near the PIE event;
- SIC-2 closure timing in the interval between the PIE and 25 sec after.

Regarding the quantitative impact of this strategy, the SIC-2 closure timing must be evaluated more deeply. Closing the valve shortly after the PIE will decrease the HTO released, but a delayed valve closure will also bring lower temperatures excursion of the FW. The relative impact of the SIC-2 timing is higher for the HTO released than for the FW temperature. In the interval between 7 s and 13 s the HTO released increases with time on an average of 10 %. While the FW temperature in the same interval increases with an average of 0.25 %.

VII. SUMMARY AND CONCLUSIONS

The simulation demonstrated a first successful application of the newly coupled procedure between RAVEN and MELCOR to assess safety through a Dynamic Event Tree. This application provided insights on how the timing of

the RD procedure and the SIC-2 valve triggering closure could affect the accident sequence focusing on two figures of merits: the HTO released from the WCS and the maximum temperature reached by the FW. The result highlighted that the ramp down procedure for plasma shutdown needs to be started soon after the PIE. At the same time, the SIC-2 valve closure could be delayed until 25 s to bring beneficial impacts on the FW temperature transient, or reduced to 7 s to drastically reduce the HTO released.

The successful deployment of the new methodology developed could have a great significance for other fusion works on safety designs. Other general thermal-hydraulics phenomena could be included in the DET analysis, investigating how a set of initial conditions could influence the accident scenario. The DET methodology could be used for an optimization strategy study during an accident scenario.

VIII. ACKNOWLEDGMENTS

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Matteo D'Onorio received his MSc degree in Energy and Nuclear Engineering in 2016 and disserted his Ph.D. thesis on safety and uncertainty quantification studies for fusion and fission nuclear power plants in 2020. He also worked in a consulting company as a data scientist. He was awarded a EUROfusion engineering grant to perform safety studies for the EU-DEMO reactor in 2020. He is currently a research fellow at the Sapienza University of Rome. His research activity mainly focuses on safety studies and modeling of multi-physics phenomena in nuclear reactors.



Tommaso Glingler received his MSc degree in Energy and Nuclear Engineering in 2021. Currently, he is a Ph.D. student at the Sapienza University of Rome. His Ph.D. activities are focused on performing safety analyses simulation for nuclear power plants. He participates as a researcher for the ongoing design basis accident analysis for the EU-DEMO reactor collaborating with the EUROFUSION consortium. Parallel research activities focus on the developing of the interface between MELCOR and RAVEN to assess dynamic probabilistic assessment of nuclear power plants.



Fabio Giannetti received his MSc degree in Energy and Nuclear Engineering in 2010 and a Ph.D. in Energy Engineering in 2014. He is currently a researcher at the Sapienza University of Rome. He is a lecturer in Nuclear Safety and Emergency Systems, Nuclear Technology Design, Nuclear Power Plants, Numerical Simulations for Nuclear Systems, and Fundamentals of nuclear engineering for astronautics. His research activity is focused on two-phase thermal-hydraulic transient analysis based on system TH computer programs. He is a member of UIT (Italian Union of Thermal-Hydraulics).

He is involved, in collaboration with ENEA, in the validation of such codes in liquid metals and the developing of a fusion version of RELAP5/mod 3.3 (for liquid metals and helical coil steam generators) and is a member of EU DEMO WCLL Breeding Blanket and Balance of Plant design team and ITER WCLL Water Cooling System for the Test Blanket System design team. He is also involved, in collaboration of Idaho National Laboratory (USA), in the validation of PHISICS/RELAP5-3D NK-TH coupled code for fast reactors mainly through the IAEA CRP Benchmark Analysis of FFTF Loss Of Flow Without Scram Test.



Gianfranco Caruso received his Master Degree in Nuclear Engineering in 1984 and Ph.D. in 1989. He is currently Full Professor in Nuclear Engineering. He is a member of the Scientific Council of International Center of Heat and Mass Transfer (ICHMT), a member of UIT (Italian Union of Thermal-Hydraulics) and a member of the European Academy of Sciences and Arts. He is "Subject Editor" for "Heat and Mass Transfer" in the Editorial Board of the journal "Latin American Applied Research (LAAR)". He participated as a researcher on several national and international projects. He is actually the research group leader in ongoing international projects and the reference person for Sapienza

research activities in the EUROFUSION Consortium framework (H2020 and Horizon Europe Actions). Since 1984 he acquired expertise in the following topics, documented mainly by his scientific publications (over 200 in international and national Journals and Conferences and several technical reports): advanced heat transfer and thermal-hydraulics in fission and fusion nuclear plants; magnetohydrodynamics; two-phases heat transfer and flow; design of components and systems for energy production plants; studies on thermophysical properties of fluids; heat transfer equipment design; thermodynamic cycles of nuclear power plants; nuclear safety in fission and fusion plants. His recent activity is mainly focused on safety analyses for fusion reactor plants.