



Original Article

On the use of time-dependent success criteria within risk-informed analyses. Application to LONF-ATWS sequences in PWR reactors

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ABSTRACT

The classical Probabilistic Safety Analysis (PSA) does not include any time dependence explicitly. However, the success criteria (SC) could evolve during the cycle for some initiating events. In that sense, there is a type of sequence in which this time-dependency is quite important, the family of Anticipated Transient without Scram (ATWS) sequences in Pressurized Water Reactors. Therefore, a new risk-informed approach is proposed in this paper, which makes it possible to obtain the time-dependent SC evolution of the safety functions affected by the Moderator Temperature Coefficient (MTC) value. Then, the evolution of the ATWS conditional core damage probability (CCDP) could be obtained using a PSA model. To quantify the CCDP, the average values of the time-dependent failure probabilities must be computed. Finally, the comparison between the CCDP obtained through the application of the classical PSA approach and the new one makes it possible to quantify the impact of time-dependence on the SC of the headers that this new risk-informed ATWS approach can provide.

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1. Introduction

The classical Probabilistic Safety Analysis (PSA) does not include any time dependence explicitly, although for a given initiating event the Event Tree (ET) headers are arranged following the expected order of actuation of the corresponding safety systems. On the other hand, there is a set of methodologies that use the so-called Dynamic ETs that include the time-dependence of the headers. Unfortunately, none of these methodologies considers the potential evolution of the success criteria (SC) from the Beginning of the Cycle (BOC) to the End of the Cycle (EOC). This dependency is quite important for a specific kind of sequences such as the Anticipated Transient without Scram (ATWS) in Pressurized Water Reactors (PWR).

In classical PSA, the ATWS ET usually includes a header related to the Moderator Temperature Coefficient (MTC). The failure of this header represents the percentage of the fuel cycle time during which the MTC value exceeds a certain critical value (this value is

plant-dependent but is usually above -15 pcm/K in a PWR Westinghouse design, PWR-W), see [1]. This critical MTC is a value of MTC above it, the Reactor Coolant System (RCS) pressure cannot be guaranteed that will not exceed the pressure acceptance criterion (ASME Service Level C pressure of 220.63 bar is assumed to be to an unacceptable plant condition during ATWS sequences, see [2]) even if the SC of the other headers are met. That period of time is called the Unfavorable Exposure Time (UET) and typically does not exceed the 1% of cycle time in PWR-W, which is assigned to the failure probability of the MTC header.

Given that it is possible to establish a relationship between the current MTC value and the performances of the safety systems represented through the other headers of the classical ET, in this new risk-informed approach, it is proposed to obtain the function associated with the time-dependent SC of the headers affected by the value of MTC. Then, the time dependence of the failure probabilities of the affected headers can be obtained from the previous step and the fault tree (FT) models, and finally, the average failure probability of each header would be the result of integrating the time-dependent probabilities across the cycle.

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Acronyms	
AFWS	Auxiliary Feed Water System
AMSAC	ATWS Mitigation System Actuation Circuitry
ATWS	Anticipated Transient Without SCRAM
BOC	Beginning Of Cycle
CCDP	Conditional Core Damage Probability
CD	Core Damage
EOC	End of Cycle
ET/FT	Event/Fault Tree
HPSI	High Pressure Safety Injection
IAPWS-IF97	International Association for the Properties of Water and Steam Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam
LONF	Loss Of Normal Feedwater
MBLOCA	Medium-Break Loss Of Coolant Accident
MOC	Middle of Cycle
MTC	Moderator Temperature Coefficient
NPP	Nuclear Power Plant
PORV	Pilot Operated Relief Valve
PZR	Pressurizer
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
SD	Steam Dump
SG	Steam Generator
SV	Safety Valve
SC	Success Criteria
TT	Turbine Trip
UET	Unfavorable Exposure Time

This paper is organized into four sections. The next section is dedicated to the application of the classical PSA approach, including a best-estimate analysis of ATWS ET. The third section corresponds to the application of the new time-dependent SC approach to ATWS sequences. In the last section, some conclusions are drawn.

2. Classical tools and methods

The main aim of this section is to perform an analysis of the ATWS event using the classical PSA approach. In Section 2.1, the reader can find firstly a description of the used PSA model, the classical SC deployed, and the hypotheses considered in this analysis. In addition, several best-estimate simulations have been performed to demonstrate the sometimes large conservativeness of certain hypotheses made in the PSA model. In that sense, a thermal-hydraulic base case has been specifically developed, based on the full plant model described in Section 2.2, for modeling the successful sequence of the classical ATWS ET, see Section 2.3. Finally, the results obtained are presented in Section 2.4.

2.1. Classical Probabilistic Safety Analysis (PSA) reference case

The classical PSA approach relies mainly on the use of ETs and the FTs models to compute the Conditional Core Damage Probability (CCDP) upon the occurrence of a specific event, in this study, the Loss Of Normal Feedwater along with an ATWS (LONF-ATWS) event. A LONF-ATWS ET is usually built considering the common safety systems used in Nuclear Power Plants (NPPs) to mitigate this kind of events, and a FT is associated with each system to determine its failure probability.

The PSA model used as a reference case in this study is a self-built PSA model of a generic PWR 3-Loop Westinghouse which has been assembled employing the risk assessment code Risk Spectrum® 1.3.0., for further information regarding the PSA model see [3]. The data relating to the reliability of the different equipment or systems implemented in the model were extracted from generic data sources, see [4]. In particular, the ATWS ET implemented in the model is depicted in Fig. 1, where the following headers, and associated SC, are considered:

- **MC - MTC VALUE:** The probability of failure of this header is associated with the UET parameter introduced in Section 1. A typical bounding MTC value for this header is -15 pcm/K, which has been used in this analysis.
- **TT - TURBINE TRIP:** This represents the performance of the TT system. In this analysis, it is conservatively assumed that the

failure of this header leads directly to core damage and its failure probability is 3.64E-3.

- **AF - HEAT REMOVAL THROUGH THE SECONDARY SIDE:** This study assumes that the auxiliary feedwater system (AFWS) is comprised of 2 Motor Driven Pumps (MDPs) and 1 Turbine Driven Pump (TDP). The success of this safety function is based on the automatic start-up of the AFWS, the injection from 2 out of 2 MDPs, or 1 out of 1 TDP, to 3 out of 3 SGs and the opening of 3 out of 6 Pilot-Operated Relief Valves (PORVs)/Safety Valves (SVs) of each main steam line. The failure probability obtained for this header is 2.00E-3.
- **BA - PZR-PORVs/SVs AUTOMATIC OPENING:** The success of this safety function is based on the automatic opening of the relief and safety valves located in the pressurizer (PZR) of the RCS. This study considers that the RCS relief system is formed by 2 PORVs and 3 SVs located at the head of the PZR. In addition to that:
 - o no credit to the manual backup actions is given because of the too-short available time in this event, and
 - o the opening of at least 2 out of 2 PZR-PORVs and 2 out of 3 PZR-SVs or 3 out of 3 PZR-SVs is required (the relief capability of each PZR-SV is considered double that of 1 PZR-PORV), for the success of this safety function. The failure probability obtained for this header is 1.49E-4.
- **EB - EMERGENCY BORATION:** In the ATWS sequence of the reference PSA model, the reactor shutdown is accomplished through the boration water from the High-Pressure Safety Injection (HPSI) into the RCS cold legs, which also guarantees the subcritical condition in the long term. Therefore, the success of this header is associated with the performance of the HPSI System. In the analysis, it is considered that in the long term, the injection of 1 out of 2 HPSI pumps to 1 out of 3 cold legs is enough to reach the subcritical condition of the reactor. The failure probability obtained for this header is 5.81E-4.
- **PF: PZR-PORVs/SVs CLOSURE:** This header implements the closure of the RCS relief paths which were previously opened (header BA). The failure probability obtained for this header is 1.88E-1.
- **SF: CLOSURE OF SECONDARY CIRCUIT RELIEF PATHS:** This safety function takes into consideration the fact that the relief paths of the secondary side previously opened must be closed. The failure probability obtained for this header is 8.46E-3.

A summarizing table with the headers' definition and the associated SC adopted in the classical PSA approach previously commented is included, see Table 1. Further considerations in this table are:

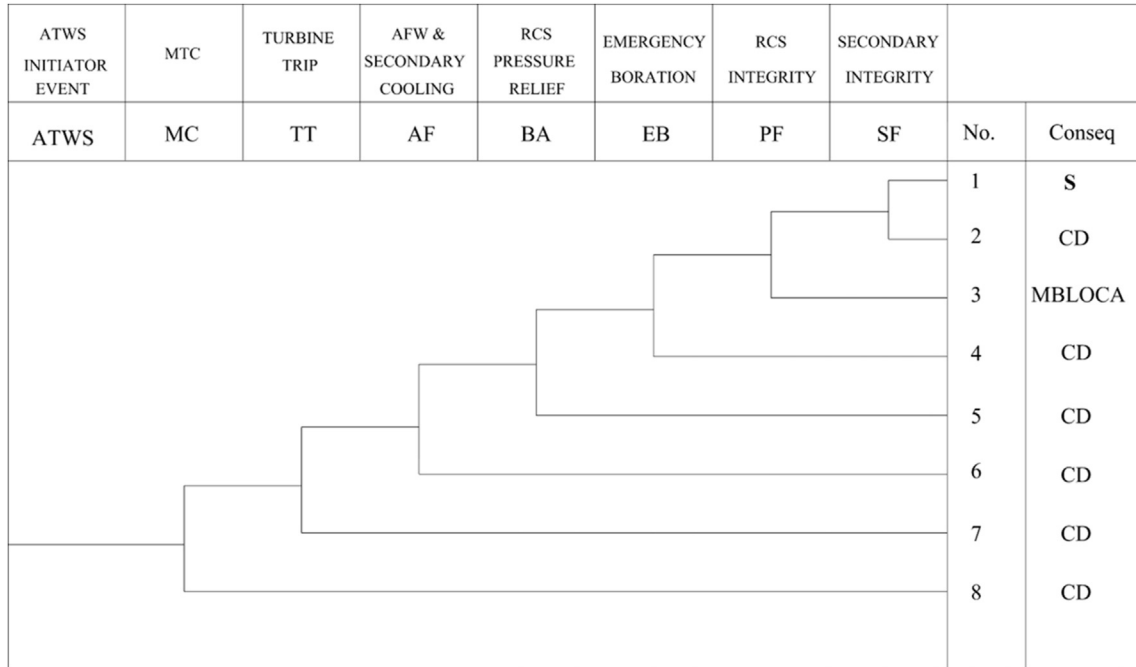


Fig. 1. ATWS Classical ET

Table 1
ATWS event SC.

Header		Success criterion
MC	MTC	MTC < -15 pcm/K; UET ≤ 1%
TT	Turbine Trip	TT must be achieved
AF	Heat Removal through the secondary side	2/2 MDPs, or 1/1 TDP, injection to 3/3 SGs & 3/6 SG-PORVs/SVs
BA	PZR-PORVs/SVs automatic opening	2/2 PZR-PORVs & 2/3 PZR-SVs or 3/3 PZR-SVs opening
EB	Emergency Boration	1/2 HPSI pumps injection to 1/3 CLS
PF	PZR-PORVs/SVs Closure	PZR-PORVs/SVs closure
SF	Closure of secondary circuit relief paths	Closure of secondary circuit relief paths

- The core damage probability of sequence 3 (see Fig. 1) has been obtained by multiplying the CCDP to the occurrence of the PF header failure by the failure probability of header PF. A failure of header PF corresponds to a situation where a PZR valve is stuck open, similar to a Medium-Break Loss Of Coolant Accident (MBLOCA) (transfer to MBLOCA ET in the reference model).
- The assumption that the failure of the TT safety function leads directly to core damage is considered to be very conservative. There are some ATWS PSA studies where this hypothesis is not assumed.

According to the reference ATWS ET, see Fig. 1, only sequence 1 is able to successfully cope with the ATWS event.

Finally, the quantification of the CCDP to the occurrence of a LONF-ATWS event is computed as the sum of the contributions of the different ET sequences with core damage (CD) consequence; the results of the CCDP are depicted in Table 2.

2.2. Full-plant TRACE PWR-W model

The reference NPP used in this study is a PWR-W with 3 loops, with a nominal thermal power of 2700 MW; the system code selected for performing the corresponding thermal-hydraulic simulations is TRACE V5.0 patch 4, [5]. It is worth noting that the modeling of the RPV and the PZR is based on the usage of TRACE 3D VESSEL component with cylindrical geometry. Whereas, the safety

Table 2
CCDP of each sequence of the ATWS ET.

Sequence	CCDP
1	SUCCESS
2	8.46E-03
3	3.40E-05
4	5.81E-04
5	1.49E-04
6	2.00E-03
7	3.63E-04
8	1.00E-02
TOTAL	2.16E-02

injection systems are modeled as boundary conditions using FILL components, and the relief systems are modeled using VALVE and BREAK components, see Fig. 2.

Regarding the ATWS transient specifically, the main features implemented in the model involve the usage of the IAPWS-IF97 steam tables, and the use of the point kinetics model in TRACE to avoid convergence issues and consider the reactivity feedbacks, respectively. Furthermore, the AMSAC actuation has also been implemented in the model (when the SG narrow range is below 12% and the turbine power is greater than 40%), being, if the case, responsible for tripping the turbine and for activating the injection from the AFWS pumps.

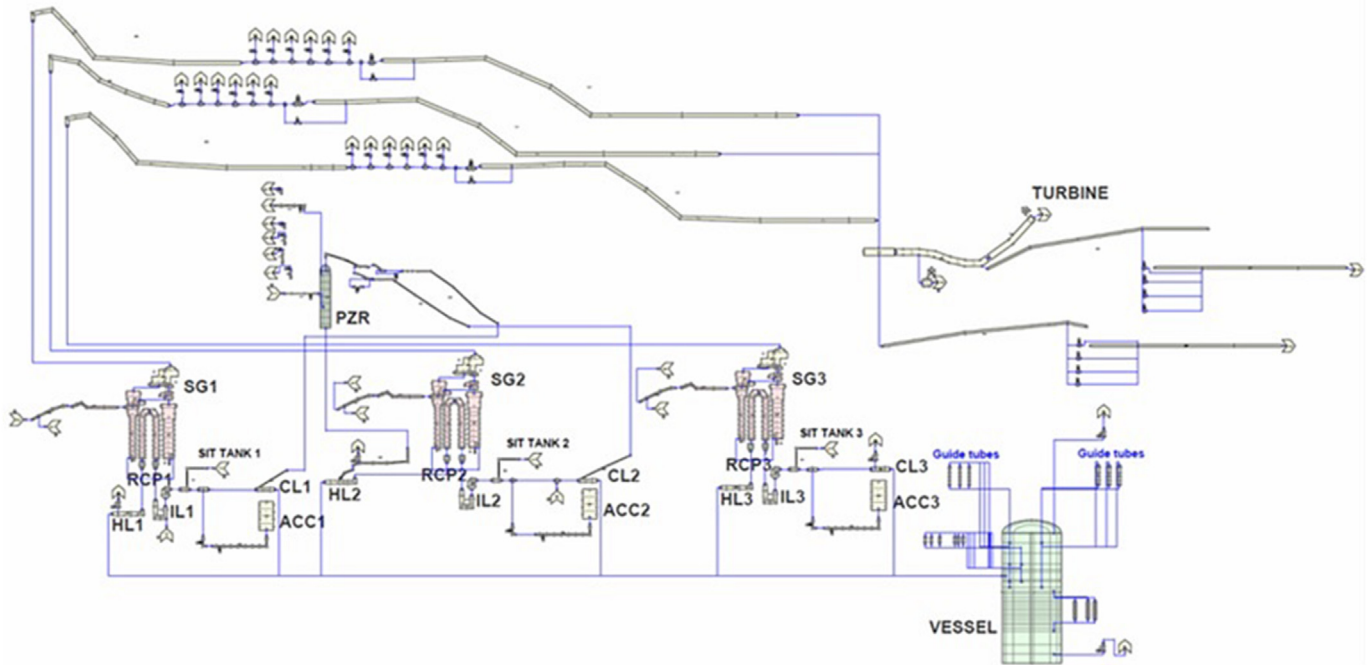


Fig. 2. Full-plant TRACE model nodalization.

The present model has been validated against steady-state, several SCRAM sequences, and verified against an extensive set of transients. For further information related to the creation and performance of this model, see [6], [7], and [8].

2.3. TH base case of the LONF-ATWS sequence

A thermal-hydraulic (TH) Base Case has been implemented within the TRACE model to represent sequence 1 of the PSA model presented in Section 2.1 (see Fig. 1), considering the respective SC of the headers representing the MTC value, the injection capacity of AFWS, the RCS relief capacity and the performance of the HPSI system. A summary of the steady-state calculation is shown in Table 3 (see Table 4).

Further hypotheses implemented in the TRACE model for this base case consists of a combination of the regular deterministic safety analyses hypotheses and the PSA SC (see [9], [10], [11], [12], [13] and [14]) are the following:

- D1. The MTC value is -15 pcm/K, corresponding to BOC conditions.
- D2. Initially, the reactor is at 100% of its nominal power. This is because this sequence is not considered to be a design basis accident, and then no power uncertainty (e.g. 2%) is applied.
- D3. No automatic reactor trip occurs.
- D4. No automatic/manual control rod insertion occurs as reactor coolant temperature increases.
- D5. No manual Reactor Coolant Pumps (RCPs) trip is performed.
- D6. Main Feedwater mass flow drops to zero within the first 4 s of the transient.
- D7. The HPSI injection capacity is limited to 1 pump (header EB success criterion).
- D8. TT occurs 30 s after the start of the transient and after another 30 s, the AFW system injects at 2 MDPs capacity (48 kg/s) due to the AMSAC actuation (headers TT and AF SC).
- D9. The primary pressure relief capacity is limited to 3 PZR-SVs (header BA success criterion).

Table 3
Steady State values comparison.

Parameters	Values	
	Reference NPP (100%)	TRACE model (100%)
Core power (MWt)	2700	2700
PZR pressure (MPa)	15.5	15.5
PZR level (%)	56.3	55.6
RCS mass flow rate (kg/s)	-	4763.2 (per loop)
Average RCS temperature (K)	581.6	581.2
SG pressure (MPa)	6.79	6.79
MFW mass flow rate (kg/s)	491.7	492.8

The simulation starts with a steady-state calculation of 5100 s and then 4 s later, the main feedwater mass flow is completely lost (i.e., LONF event). As a result, the SGs capacity to remove the core heat generated is degraded, leading to an increase in RCS pressure and temperature, see Fig. 3 and Fig. 4. On the secondary side, the amount of steam generated and the pressure increase, as it is shown in Fig. 5, leading to a decrease in the SG water level up to the 12% of the narrow level AMSAC set-point; 3 s later the turbine is tripped by the AMSAC signal, and the Steam Dump (SD) valves are opened.

Subsequently, the nuclear power decreases down to 95% due to the negative reactivity feedback of the moderator temperature, see Fig. 6 and Fig. 7. However, the pressure on the secondary side keeps rising and the setpoint of the SG-PORVs is reached causing its opening, as it is depicted in Fig. 5. Meanwhile, the RCS pressure increases as well, reaching the setpoint of the PZR-SVs; the three available PZR-SVs (the actuation of the PZR-PORVS is neglected in the base case) open to control the RCS pressure, see Fig. 3. Subsequently, the pressure in the secondary side continues to increase, despite the opening of SGs-PORVs, and the setpoint of SGs-SVs is reached; the SG-SVs open, and a few seconds later the maximum value of the secondary pressure is reached, see Fig. 5.

After 30 s from TT and per the D8 hypothesis of the analysis, 2

Table 4
Base Case events.

Time after the LONF (s)	Main events
0	LONF
4	MFW flow fully stopped
20	Beginning of PZR sprays actuation
25	SGs U-tubes begin to uncover. SG Low narrow range level signal (17.6%)
27	AMSAC signal (Low-Low SG narrow range level (12%) and nuclear power > 40%)
30	TT induced by AMSAC signal
30.3	SD valves open (TT+0.3 s)
35	95% of the nominal Nuclear Power
36	SG-PORVs open (7.81 MPa)
40	RCS pressure reaches PZR-SVs set point (17.34 MPa)
47	SG-SVs open (8.4–8.8 MPa)
60	AFW flow injects to SGs. Hypothesis of the analysis (TT + 30s)
90	PZR solid
97	Main steam line isolation signal (Compensated low steam line pressure signal, 4.81 MPa) Minimum secondary inventory
110	Maximum RCS pressure (21.7 MPa) 35% Nuclear power
149	HPSI injection starts
166	PZR bubble
169	Maximum average RCS temperature (631 K) Beginning of RCS boiling
206	PZR-SVs fully closed (17.34 MPa)
900	End of the simulation

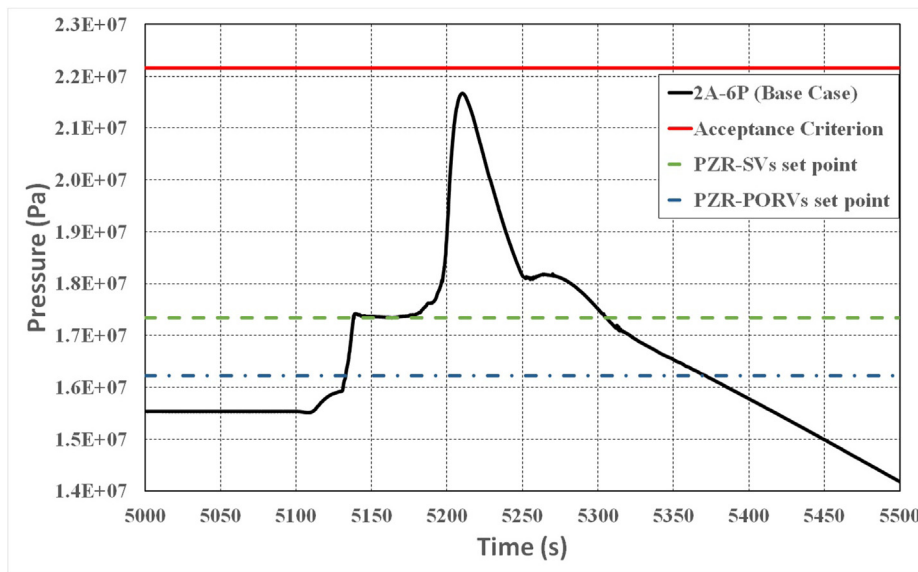


Fig. 3. RCS pressure (sequence 1).

out of 3 AFWS pumps start to inject into the secondary side of the SGs, which makes it possible to remove the heat from the primary side. Afterward, the PZR becomes solid and almost 100 s after the beginning of the transient, the signal associated with the compensated low pressure in the secondary side (E signal) is triggered causing the isolation of the main steam lines, see Fig. 5. A few seconds later, the RCS pressure peak is reached, and nuclear power reduces to 35% of the nominal value. From this moment on, the RCS pressure decreases, so the HPSI system can inject water into the RCS cold legs and, therefore, the RCS temperature starts also decreasing. Nevertheless, the RCS water starts boiling due to the sharp reduction of the RCS pressure, up to the setpoint of the closure of the PZR-SVs, 206 s after the LONF occurrence. Finally, the nuclear reactor becomes subcritical due to the cumulative action of the Boron solved in the RCS, and the nuclear power tends to zero in the long

term, as it is demonstrated in Figs. 7 and 8, and Fig. 9.

In addition, it should be noted that the transient could be divided into two stages: the short term, which is focused on the pressure peak period of time (Figs. 3–7), and the long term where the main goal is the demonstration that the nuclear reactor does not reach criticality again (Figs. 8 and 9).

2.4. Best-estimate quantification of the classical ET

This section presents several best-estimate (BE) simulations that have been carried out in order to assess the impact of:

- the usage of different time-dependent MTC functions of the fuel cycle time on the failure probability of the MC header, see Section 2.4.1, and,

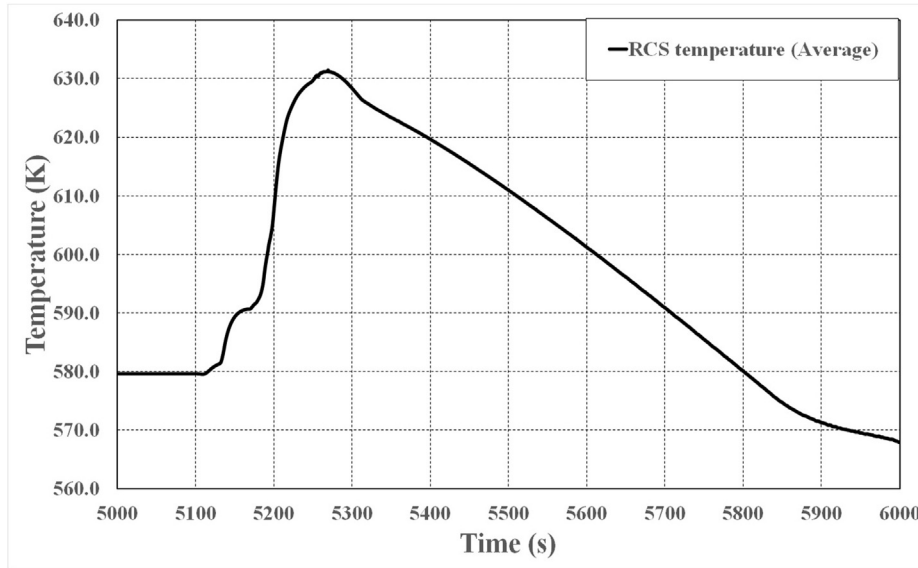


Fig. 4. RCS temperature (Sequence 1).

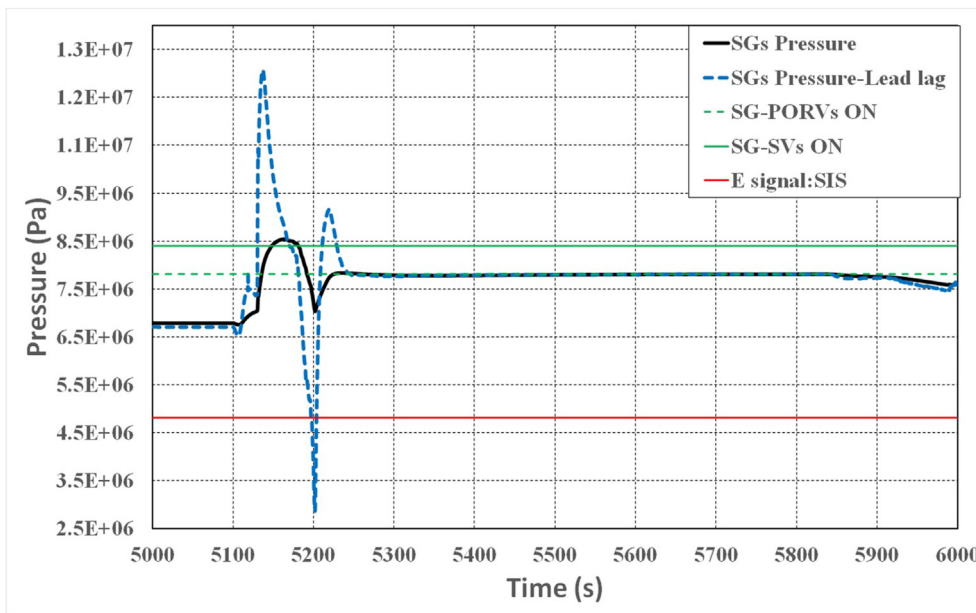


Fig. 5. Secondary pressure (sequence 1).

- the failure to close the secondary side relief paths previously opened, see Section 2.4.2.

Finally, Section 2.4.3 is devoted to the quantification of the risk of those BE cases and to comparing the results obtained with those obtained using the classical PSA approach (section 2.1).

2.4.1. Assessment of the MC header

As stated above, the critical MTC value is defined as the least negative MTC value for which the RCS pressure peak produced by the occurrence of the LONF-ATWS event remains below the acceptance criterion. A value of -14 pcm/K for this critical MTC is obtained by running different simulations with TRACE. Afterward, aiming at obtaining the number of days of the fuel cycle during which the MTC value is exceeding the obtained critical MTC, a

comparison between the critical MTC values and two time-dependent MTC functions considered in the literature is made. The first one is a conservative MTC evolution used by the Westinghouse Owners Group in reference [15] which will be denoted by WOG-HRC, and the latter consists of a function typically used in best-estimate calculations, see [16], and it is defined as PWR-W3L, see Fig. 10.

The next step consists of the UET calculation and its probability. To do so, and according to Fig. 10, the critical MTC criterion is violated during 2.1 days in the PWR-W3L case and during 145 days in the WOG-HRC case. As the fuel cycle length is 525 days, the probability of each UET obtained for each MTC function is as follows:

$$UET (PWR-W3L) = 2.1 \text{ days} / 525 \text{ days} = 4.00E-03$$

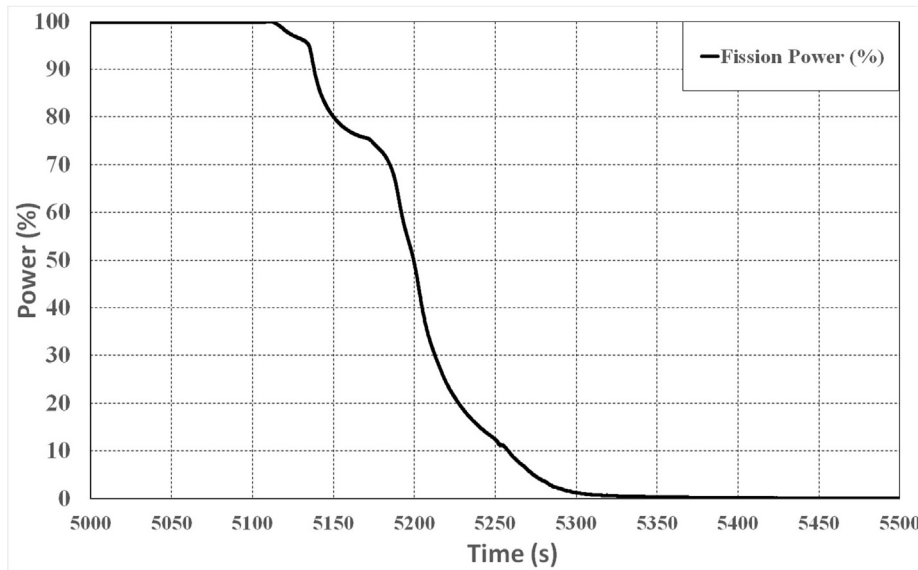


Fig. 6. Nuclear power (Sequence 1).

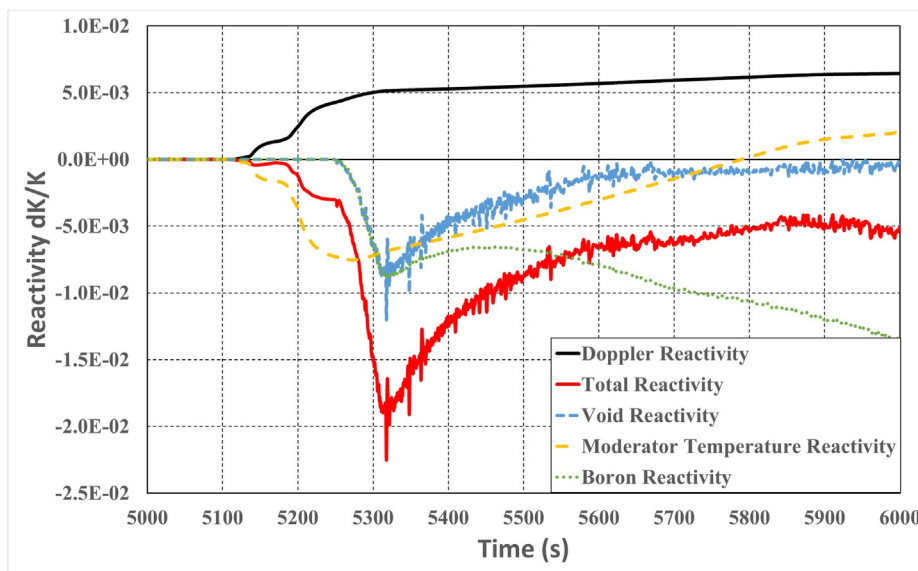


Fig. 7. Reactivity feedback (Sequence 1).

UET (WOG-HRC) = 145 days / 525 days = **2.76E-01**

2.4.2. Assessment of the failure to close the secondary side relief paths

As stated in Section 2.4, a sensitivity analysis applied to the Base Case sequence 1 has been performed to assess whether the failure of the SF header leads directly to core damage or not (Sequence 2 in the classical ET). To do so, not only the failure to close the SG-SVs is implemented in the TRACE model, but the evolution of the MTC and the Boron concentration in the RCS during the fuel cycle are also considered: BOC, middle of the cycle (MOC), and EOC conditions; Table 5 summarizes the values of MTC and Boron concentration that have been analyzed.

From the results presented in Fig. 11, it is demonstrated that the failure to close an SG-SV has no impact on the primary pressure

peak induced by the LONF-ATWS sequence. Nevertheless, in the long-term, the failure to close the relief paths in the secondary side also causes an excessive cooling of the reactor coolant, introducing an important amount of positive reactivity in the core, and so the total reactivity of the core in the long-term needs to be assessed. As expected, the nuclear reactor could become supercritical for several minutes causing nuclear power to increase temporarily, see Fig. 12. However, in the long-term, the nuclear power tends to zero and the reactor becomes subcritical for all the considered situations, as can be seen in Figs. 12 and 13.

Finally, according to the results obtained in this section, sequence 2 does not lead to core damage and, consequently, it is removed from the quantification process of PWR-W3L and WOG-HRC cases.

2.4.3. Best-estimate quantification of risk

This section presents the results of the CCDP quantification of

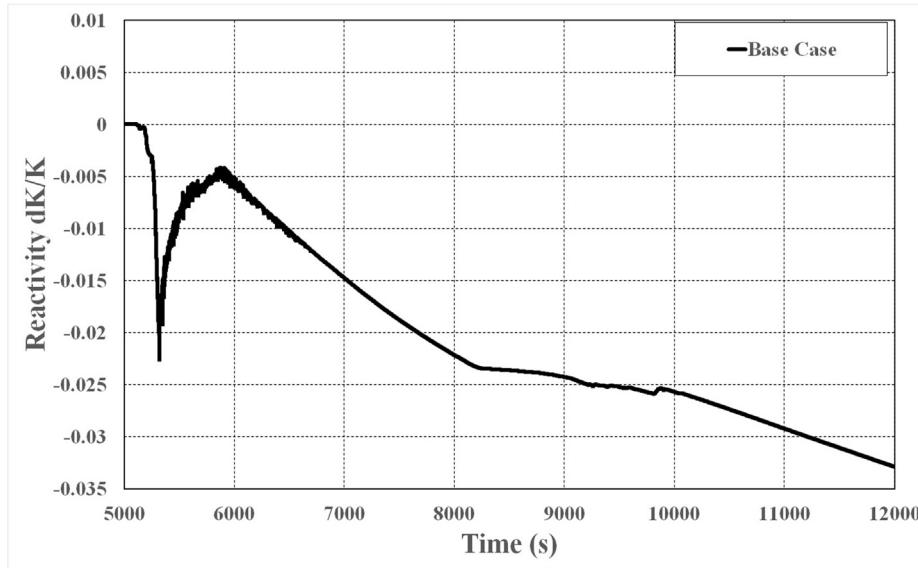


Fig. 8. Total Reactivity in the long-term (Sequence 1).

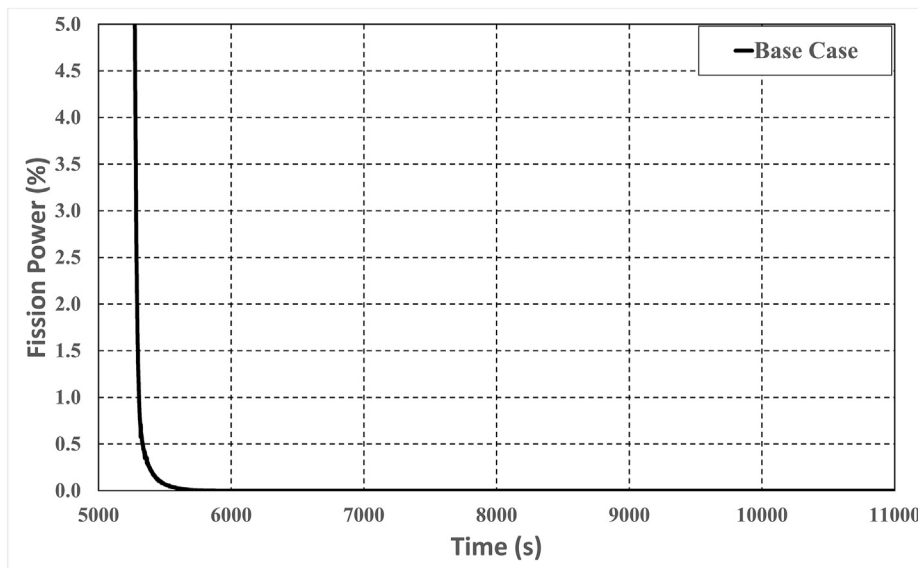


Fig. 9. Nuclear Power in the long-term (Sequence 1).

the cases described in Sections 2.4.1 and 2.4.2; Table 6 summarizes the main outcomes and highlights the sequences with higher probability contribution to the CCDP.

Table 6 shows as well that one of the features with the most influence on the ATWS CCDP value is the time-dependent MTC function. The CCDP value obtained for the best estimate MTC function is one order of magnitude lower than the value obtained by employing the classical PSA approach, whereas the CCDP value obtained using the conservative MTC function is one order higher.

Likewise, sequence 2 is considered a successful one due to the results obtained in Section 2.4.2 and as a consequence, sequence 6 becomes the second one in order of relevance for the studied cases (Table 6).

Finally, it is worth noting that, despite the results obtained in this section, the CCDP resulting for both cases, the one associated with the usage of the best estimate MTC function and the

conservative one, using the new proposed time-dependent SC approach will be significantly lower than the CCDP values obtained by the classical PSA approach, as will be demonstrated in the following sections.

3. Time-dependent success criteria approach

The new approach proposed hereby consists of a risk-informed methodology that allows obtaining a more accurate value of the CCDP. This time-dependent SC approach is based on the usage of a realistic time-dependent MTC function along with a detailed analysis of the safety systems configuration probabilities employing the expanded ET concept (EET); further information regarding EETs is presented in the section 3.4. It comprises the following steps (see also Fig. 14):

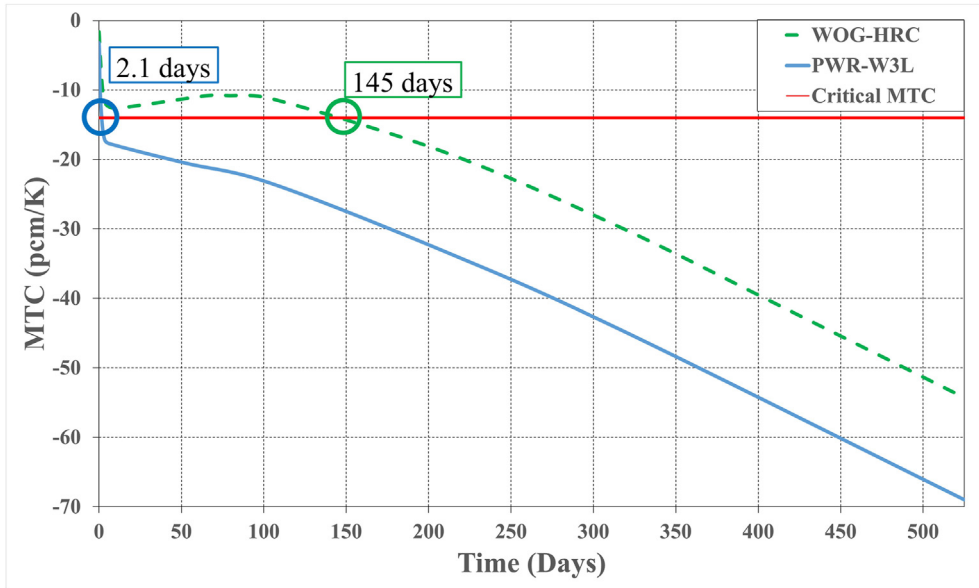


Fig. 10. MTC vs Time (Days).

Table 5

MTC and Boron Concentration values of the cases considered at BOC, MOC, and EOC.

	MTC (pcm/K)	Boron concentration (ppm)
Sequence 1: Base Case.	-15	1500
Sequence 2: Case 1 (BOC with failure to close of a SG-SV).	-15	1500
Sequence 2: Case 2 (MOC with failure to close of a SG-SV).	-40	825
Sequence 2: Case 3 (EOC with failure to close of a SG-SV).	-70	150

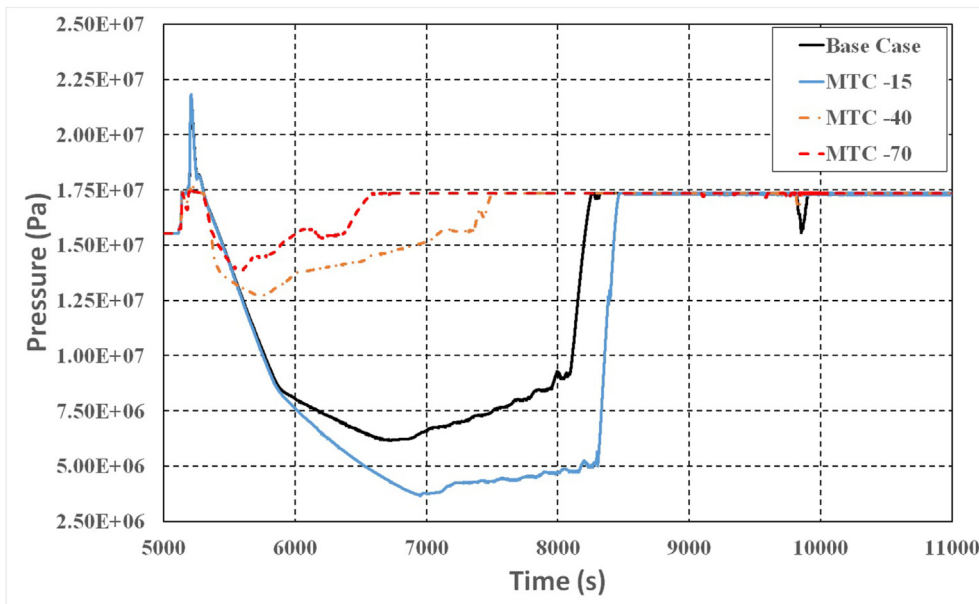


Fig. 11. RCS pressure peak vs Time (Sequence 2).

S1. Critical MTC value calculation for each possible configuration of AFW pumps availability and primary relief capacity, see Section 3.1.

S2. MTC-dependent SC determination using the results obtained in S1, see Section 3.2

S3. The relationship between SC and time is established through the correspondent MTC(t) functions, and from the results obtained in S2, see Section 3.3.

S4. Calculation of the probability for each configuration of AFW pumps availability and primary relief capacity through the EET concept, see Section 3.4.

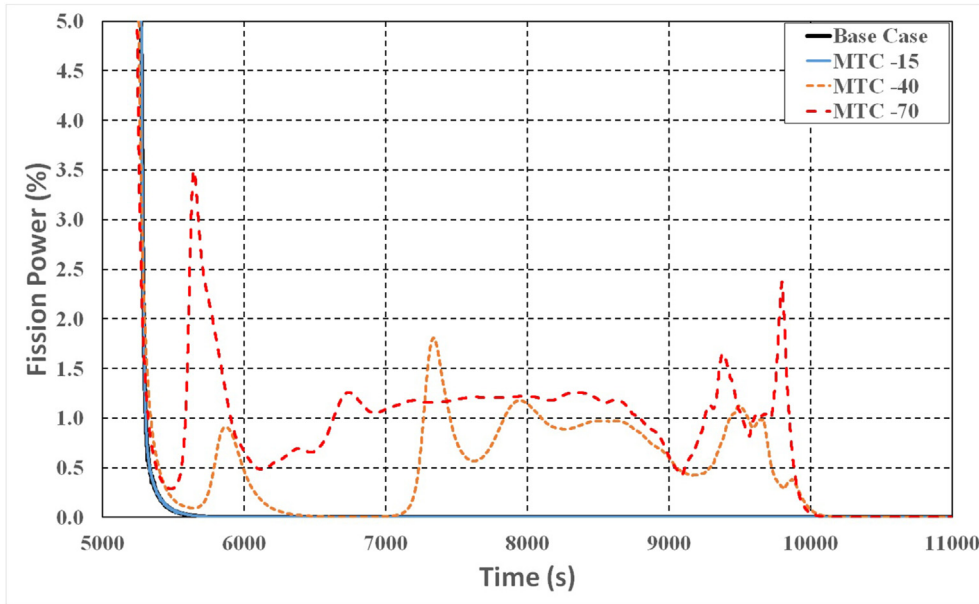


Fig. 12. Nuclear power vs Time (Sequence 2).

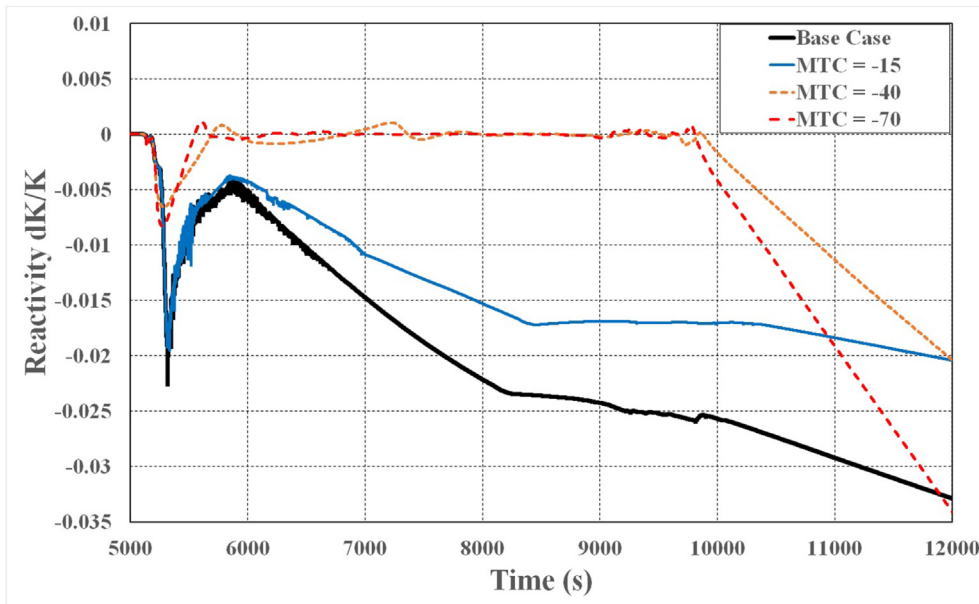


Fig. 13. Reactivity vs Time (Sequence 2).

Table 6
CCDP quantification results for the PWR-W3L and WOG-HRC cases (classical PSA approach).

Seq.	CCDP		
	Classical PSA	BE PWR-W3L	Bounding WOG-HRC
2	8.46E-03	SUCCESS	SUCCESS
3	3.40E-05	3.40E-05	3.40E-05
4	5.81E-04	5.81E-04	5.81E-04
5	1.49E-04	1.49E-04	1.49E-04
6	2.00E-03	2.00E-03	2.00E-03
7	3.63E-04	3.63E-04	3.63E-04
8	1.00E-02	4.00E-03	2.76E-01
TOTAL	2.16E-02	7.13E-03	2.79E-01

S5. Calculation of the failure probability of the time-dependent AF+BA(t) header using the results obtained in S3 and S4, see Section 3.5 (MC header is implicitly considered in the time-dependent failure probability of the AF-BA(t) header).

S6. Quantification of the CCDP integrating the time-dependent failure probabilities obtained in S5, see Section 3.6.

3.1. Critical MTC calculation for each AF-BA configuration (step 1)

The critical MTC of each AF-BA configuration is calculated through an MTC sensitivity analysis with TRACE, see Fig. 15. Then, a detailed analysis of the impact of the AF and BA capability on the critical MTC is carried out, see Fig. 16 to Fig. 19.

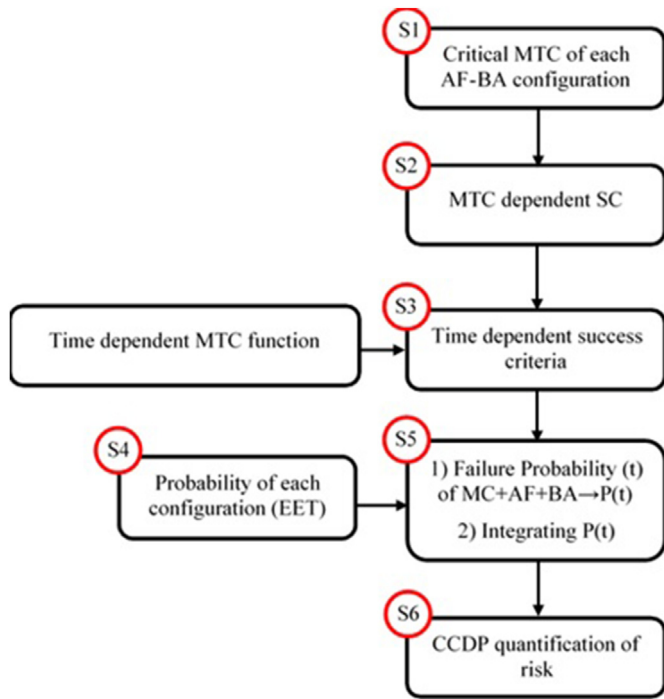


Fig. 14. Time-dependent SC methodology flow chart.

Hypotheses used in these TRACE calculations are:

- The absolute value of the MTC is restrained only to integer values in pcm/K.
- The critical MTC values are allowed to vary within the range from 0 to -70 pcm/K and, if an AF-BA configuration had an associated critical MTC lower than -70 pcm/K as the values in grey in the last column of Table 7, it will be considered that such configuration directly leads to core damage.

- It is assumed that the cases with no injection from the AFWS also lead to core damage since in such cases the long-term cooling cannot be assured without considering the successful manual feed and bleed maneuver performed by the operator, which is out of the scope of this study, see the rows in grey in Table 7.
- It is assumed that the TDP of the AFW system injects a total mass flow equivalent to twice the injected by 1 MDP of the AFW system. Thus, the AFW system flow rate capacity would be represented as a discrete range from 0 to the flow rate equivalent to 4 AFW-MDPs injection capacity (i.e., 5 possible configurations).
- The relief capability of each PZR-SV is considered double that of 1 PZR-PORV. Thus, the primary relief system is represented in a discrete range from 0 to the relief capacity equivalent to 8 PZR-PORVs (8P), with nine possible configurations.

Consequently, a total of 45 possible interconnected AF-BA configurations have been considered. In addition, depending on whether the turbine is successfully tripped or not, a total of 90 different configurations have been finally analyzed with the TRACE model, to compute the corresponding critical MTC values. Table 7 summarizes the results of this sensitivity analysis. Relevant conclusions drawn from this step, see Table 7, are the following:

- The failure of the TT safety function has a negative impact on the critical MTC of a specific AF-BA configuration, as a lower MTC value is obtained in comparison to the case with a successful TT.
- The effect in the RCS pressure peak of BA performance is sharper than the AF one, see Figs. 16 and 17. In other words, the primary relief system plays a more important role in the mitigation of the RCS pressure peak triggered by the ATWS event than the one played by the AFW system. However, it is not possible to establish this as a general rule for any PWR due to the heterogeneity found in the AFW and primary relief systems capacities amongst different NPPs.
- Finally, Fig. 18 and Fig. 19 show the non-linear influence on the RCS pressure peak of the AFW or primary relief systems

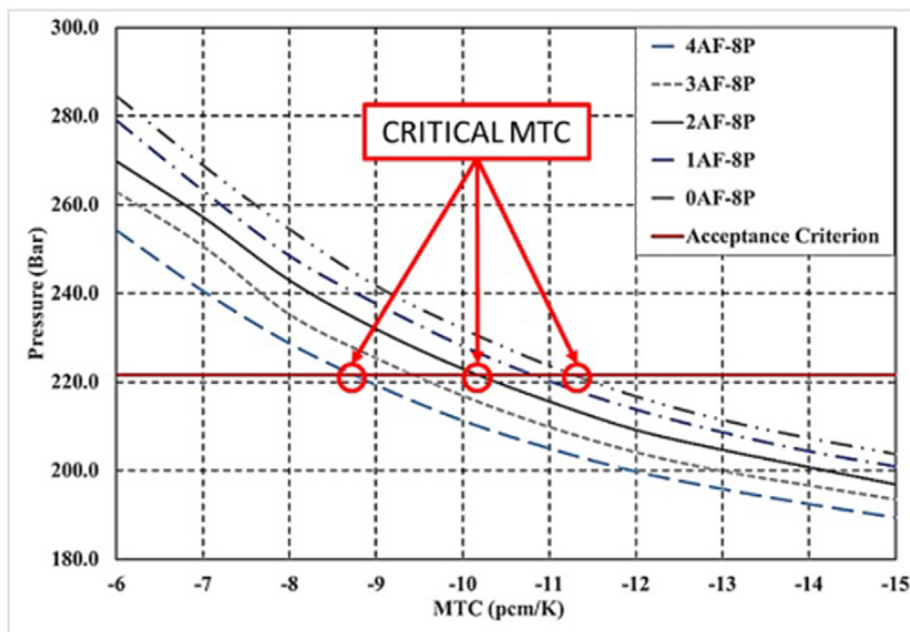


Fig. 15. Critical MTC for each AFW configuration (3 SVs + 2 PORVs, 8P case).

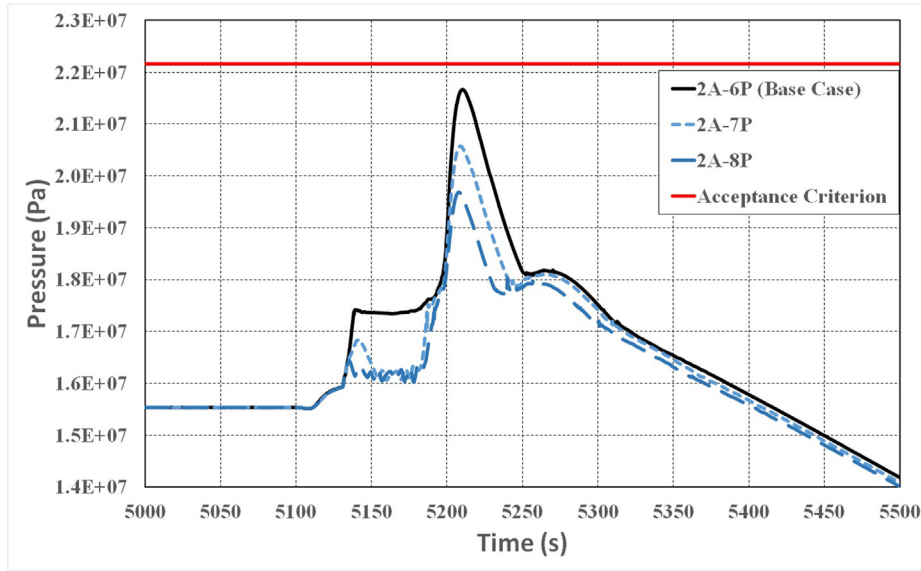


Fig. 16. RCS pressure peak for different PZR relief capacity (2 AFW-MDPs case).

Table 7
Critical MTC values.

		PZR PORVs Relief capacity										
		x8	x7	x6	x5	x4	x3	x2	x1	x0		
MDP-AFW	x4	-9	-11	-12	-15	-19	-23	-29	-36	-59	WITH TT	
	x3	-10	-11	-13	-17	-20	-26	-31	-40	-65		
	x2	-11	-12	-14	-18	-22	-28	-34	-44	<-70		
	x1	-11	-13	-15	-19	-24	-30	-37	-49	<-70		
	x0	-12	-14	-16	-20	-25	-31	-40	-57	<-70		
	x4	-10	-12	-15	-19	-23	-28	-35	-47	<-70	WITHOUT TT	
	x3	-11	-13	-16	-20	-24	-31	-39	-53	<-70		
	x2	-12	-14	-17	-22	-26	-33	-42	-60	<-70		
	x1	-13	-15	-18	-23	-28	-36	-45	-68	<-70		
	x0	-13	-15	-19	-24	-28	-37	-47	-75	<-70		

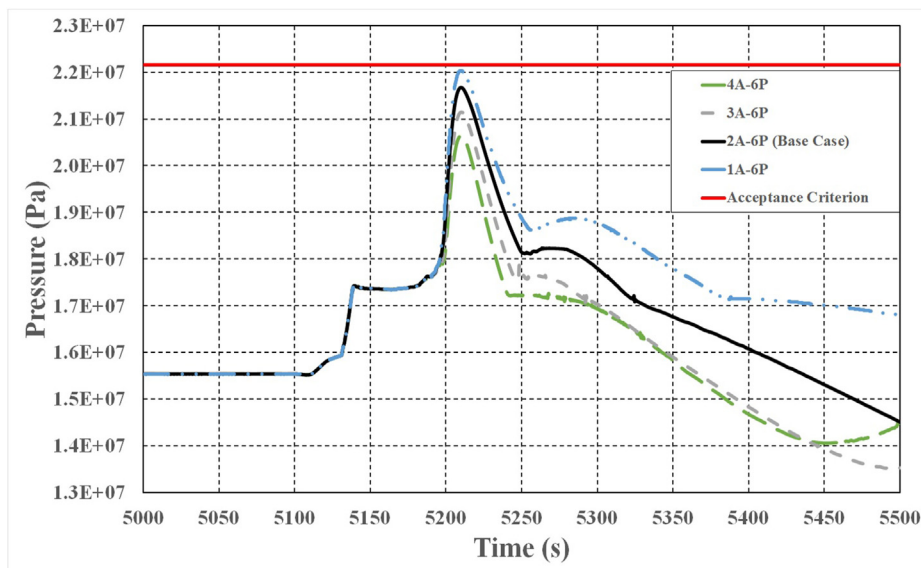


Fig. 17. RCS pressure peak for the different AFW injection capacity (6P case).

performances using the critical MTC values associated with each configuration.

3.2. MTC-dependent SC calculation (step 2))

This section identifies the dependence between the current SC and the critical MTC during a specific time interval, based on the results obtained in the previous section. To do so, the AF-BA configurations are sorted in terms of ascending critical MTC. However, as there are certain AF-BA configurations with the same critical MTC value, see Table 7, the least demanding configuration associated with a specific period is selected (when possible). For instance, if two AF-BA configurations have the same critical MTC as well as the same relief capacity during a specific time interval, then the selected configuration would be the one with the lower AFW injection need. Nevertheless, if the AF-BA configurations only have the critical MTC value in common, both SC would coexist during the corresponding period. In that case, it is important to notice that those SC are completely independent one to another and there is no way to rank them, see Table 8 and Table 9.

The fact that two or even three AF-BA configurations could deal simultaneously with the consequences of the ATWS event is the most relevant result obtained so far and the most disruptive feature of the time-dependent SC methodology in comparison with the classical one. The implications of having multiple SC coexisting in the same period are an obvious reduction in the instantaneous failure probability of the combined AF-BA safety function. This implies further enhanced flexibility in terms of the possible mitigation strategy of the consequences of the ATWS event in a generic nuclear power plant since it could be interpreted as an extension of the possible actions to be taken by the operators to mitigate the accident.

3.3. Time-dependent success criteria calculation (step 3)

Once the whole critical MTC values associated with each AF-BA configuration are calculated, see Section 3.1, and the classification of them in ascending order of MTC is performed, see Section 3.2, the instantaneous AF-BA configuration which can deal with the

consequences of the ATWS event is computed. Before that, the “temporal” component of the SC is introduced by correlating the critical MTC values associated with each AF-BA configuration, Tables 8 and 9, with the time-dependent MTC function selected, see Fig. 10. In addition, it is assumed that a specific AF-BA configuration is valid as a success criterion within a specific range of MTC values. That range is limited by the critical MTC of the AF-BA configuration itself and the critical MTC of the immediately less demanding AF-BA configuration considered as success criterion. Therefore, there is a specific interval of time associated with each success criterion or group of SC, so the time-dependent SC function must follow the same tendency as the time-dependent MTC function used.

Combining the information of both, Fig. 10 and Table 8, time-dependent SC functions for PWR-3L and WOG-HRC cases with TT are obtained, Fig. 20 and Fig. 21; corresponding cases without TT have been also obtained similarly using Fig. 10 and Table 9, instead. From these results, it is worth noticing that the SC requirements have a decreasing tendency with time for the PWR-W3L case. This implies that the current success criterion can be continuously loosened as time goes by along the fuel cycle if a PWR-W3L time-dependent MTC function is used (Fig. 20). However, in the case of using the WOG-HRC time-dependent function, although, with a similar decreasing tendency, the evolution of the SC shows a minimum and a maximum at the early stages of the fuel cycle due to the influence of the shape of such time-dependent MTC function (Fig. 21).

All in all, the obtained results show that, even with the availability of the maximum capacity of the AF-BA safety functions, it is not possible to successfully cope with the LONF-ATWS sequence during the early stage of the fuel cycle, and the number of days under those conditions is strongly affected by the time-dependent MTC function used in the analysis (i.e. 0.6 days for the PWR-W3L function and 2.3 days for the WOG-HRC, see Fig. 20).

These results highlight as well the great influence of the time-dependent MTC function upon the temporal evolution of the SC. Apart of the influence shown in the shape above, in the case of using the PWR-W3L function, Fig. 10, the SC are less demanding than in the case of using the WOG-HRC function, Fig. 10, as can be seen in Figs. 20 and 21.

Nevertheless, given that the design features of the AFW and

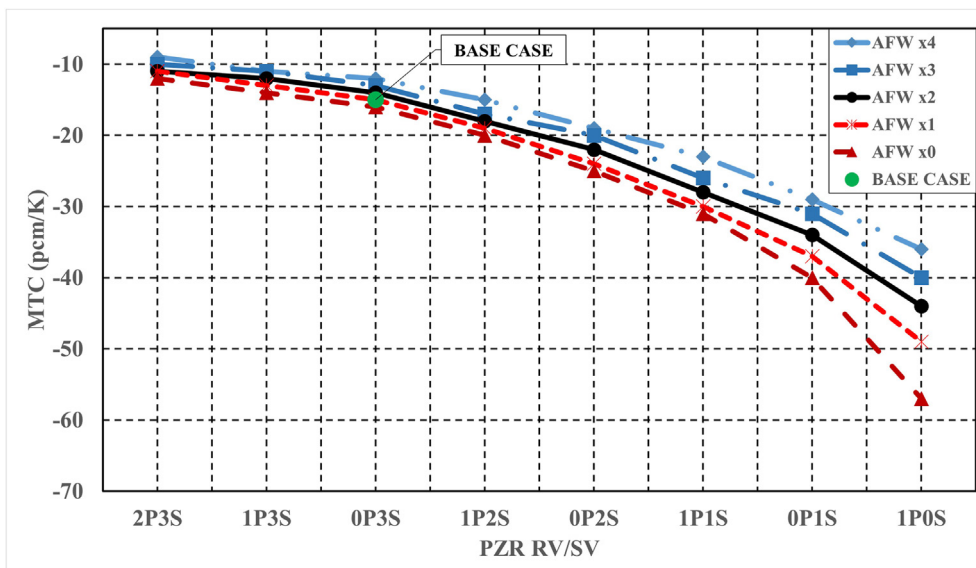


Fig. 18. Critical MTC for each configuration with TT.

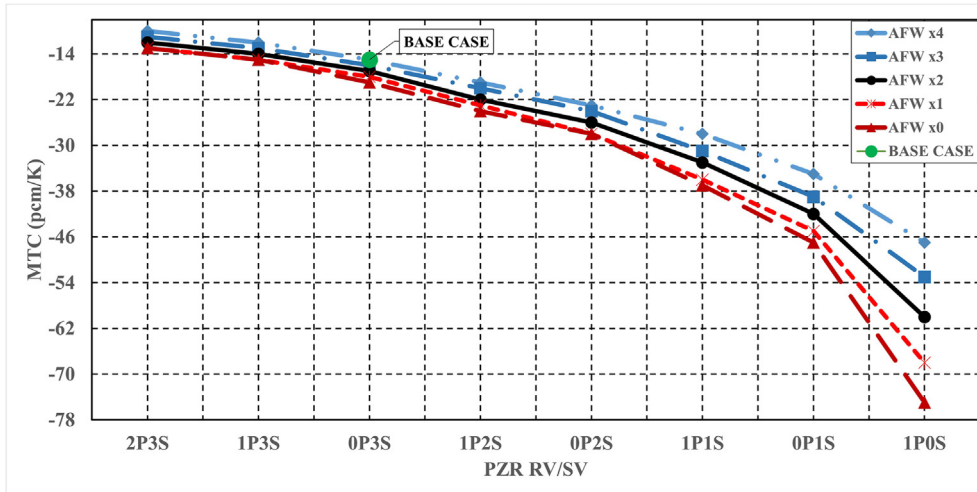


Fig. 19. Critical MTC for each configuration without TT.

Table 8
SC evolution in terms of the critical MTC value (with TT case).

MTC (pcm/K)	Success criterion
-1.6	-
-9.0	4AFW + 2P3S
-10.0	3AFW + 2P3S
-11.0	1AFW + 2P3S OR 3AFW + 1P3S
-12.0	1AFW + 2P3S OR 2AFW + 1P3S OR 4AFW + 0P3S
-13.0	1AFW + 1P3S OR 3AFW + 0P3S
-14.0	1AFW + 1P3S OR 2AFW + 0P3S
-15.0	1AFW + 0P3S OR 4AFW + 1P2S
-16.0	1AFW + 0P3S OR 4AFW + 1P2S
-17.0	1AFW + 0P3S OR 3AFW + 1P2S
-18.0	1AFW + 0P3S OR 2AFW + 1P2S
-19.0	1AFW + 1P2S OR 4AFW + 0P2S
-20.0	1AFW + 1P2S OR 3AFW + 0P2S
-22.0	1AFW + 1P2S OR 2AFW + 0P2S
-23.0	1AFW + 1P2S OR 2AFW + 0P2S OR 4AFW + 1P1S
-24.0	1AFW + 0P2S OR 4AFW + 1P1S
-25.0	1AFW + 0P2S OR 4AFW + 1P1S
-26.0	1AFW + 0P2S OR 3AFW + 1P1S
-28.0	1AFW + 0P2S OR 2AFW + 1P1S
-29.0	1AFW + 0P2S OR 4AFW + 0P1S OR 2AFW + 1P1S
-30.0	1AFW + 1P1S OR 4AFW + 0P1S
-31.0	1AFW + 1P1S OR 3AFW + 0P1S
-34.0	1AFW + 1P1S OR 2AFW + 0P1S
-36.0	1AFW + 1P1S OR 2AFW + 0P1S OR 4AFW + 1P0S
-37.0	1AFW + 0P1S OR 4AFW + 1P0S
-40.0	1AFW + 0P1S OR 3AFW + 1P0S
-44.0	1AFW + 0P1S OR 2AFW + 1P0S
-49.0	1AFW + 1P0S
-57.0	1AFW + 1P0S
-59.0	1AFW + 1P0S OR 4AFW + 0P0S
-65.0	1AFW + 1P0S OR 3AFW + 0P0S

primary relief systems are highly variable amongst different nuclear power plants, the results obtained in this section for the SC as function of time are only valid for the generic NPP considered in this study and a dedicated analysis is needed for any other NPP.

3.4. EET approach to quantify the system configurations probabilities (step 4)

In the ETs of the classical PSA approach, only two outcomes are considered from the intervention of a given system or header, either failure or success. These outcomes are computed as the probabilities of matching or not the so-called SC, which define in

Table 9
SC evolution in terms of the critical MTC value (without TT case).

MTC (pcm/K)	Success criterion
-1.6	-
-10.0	4AFW + 2P3S
-11.0	3AFW + 2P3S
-12.0	2AFW + 2P3S OR 4AFW + 1P3S
-13.0	1AFW + 2P3S OR 3AFW + 1P3S
-14.0	1AFW + 2P3S OR 2AFW + 1P3S
-15.0	1AFW + 1P3S OR 4AFW + 0P3S
-16.0	1AFW + 1P3S OR 3AFW + 0P3S
-17.0	1AFW + 1P3S OR 2AFW + 0P3S
-18.0	1AFW + 0P3S
-19.0	1AFW + 0P3S OR 4AFW + 1P2S
-20.0	1AFW + 0P3S OR 3AFW + 1P2S
-22.0	1AFW + 0P3S OR 2AFW + 1P2S
-23.0	1AFW + 1P2S OR 4AFW + 0P2S
-24.0	1AFW + 1P2S OR 3AFW + 0P2S
-26.0	1AFW + 1P2S OR 2AFW + 0P2S
-28.0	1AFW + 0P2S OR 4AFW + 1P1S
-31.0	1AFW + 0P2S OR 3AFW + 1P1S
-33.0	1AFW + 0P2S OR 2AFW + 1P1S
-35.0	1AFW + 0P2S OR 2AFW + 1P1S OR 4AFW + 0P1S
-36.0	1AFW + 1P1S OR 4AFW + 0P1S
-37.0	1AFW + 1P1S OR 4AFW + 0P1S
-39.0	1AFW + 1P1S OR 3AFW + 0P1S
-42.0	1AFW + 1P1S OR 2AFW + 0P1S
-45.0	1AFW + 0P1S
-47.0	1AFW + 0P1S OR 4AFW + 1P0S
-53.0	1AFW + 0P1S OR 3AFW + 1P0S
-60.0	1AFW + 0P1S OR 2AFW + 1P0S
-68.0	1AFW + 1P0S

advance the minimum requirements which must be met by the system to be able to accomplish its safety function.

The fact that a system success criterion must be predefined for a given sequence usually requires strong conservative assumptions and might be a significant setback when performing detailed analyses. In that sense, the EET methodology provides a tool to avoid such restrictions, computing all the potential configurations of the different safety systems as different branches in the ETs. For further information related to the EET approach, see [17], [18], [19], [20], [21].

To calculate the probability to have each specific configuration within a given system, a different FT is used combining appropriately all possible system equipment failures. For instance, if a given system were comprised of 3 pumps and the calculation of the

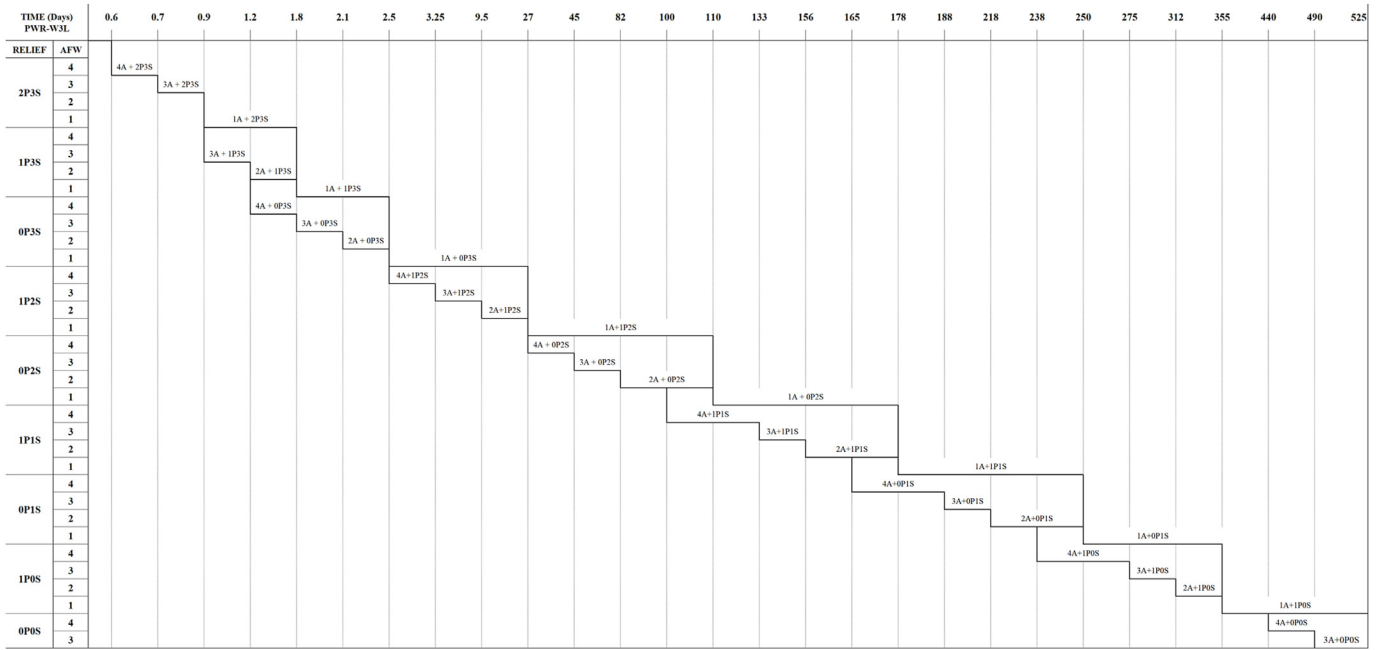


Fig. 20. Time-dependent SC of AF-BA with TT (PWR-W3L case).

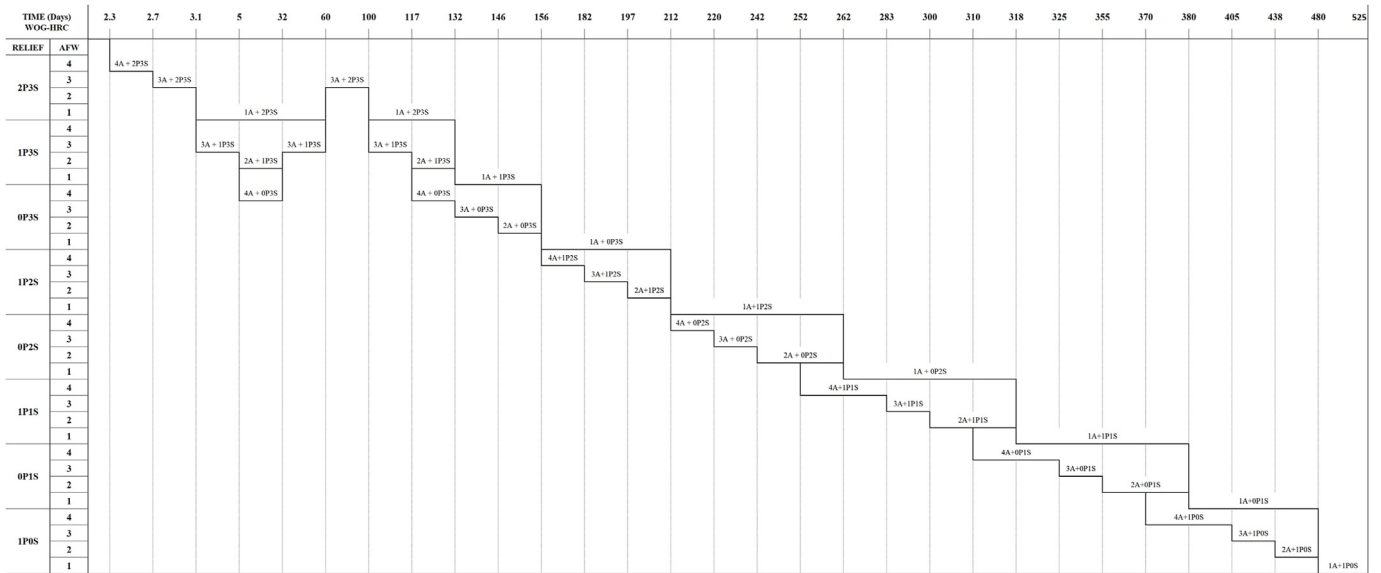


Fig. 21. Time-dependent SC of AF-BA with TT (WOG-HRC case).

probability to have available 1 pump would be performed, the FT top event could be a 2/3 gate with the failures of each of the 3 pumps as inputs.

In this study, the EET approach has been applied to the AFW system and the primary pressure relief system; the probability of each possible configuration of the AF and BA headers has been computed conditioned to the TT success/failure by using the Risk Spectrum software, see Table 10. To do so, the five possible configurations of the AFWS-MDP injection capacity in combination with the other nine correspondents to the PZR-PORVs performance described in detail in Section 3.1, have been taken into consideration for scenarios with and without TT.

On the other hand, the mechanisms that lead to the failure of each configuration for the AFWS and the RCS relief system, defined

as the minimal cut sets, are identified separately because they can be caused by different failures, see Table 11 and Table 12.

Given the EET, it is easy to calculate the probability that a given success criterion is not matched by summing all the probabilities of configurations that do not satisfy that criterion. This is particularly fitted for the present study where the system success criteria are considered a function of time and cannot be prefixed in advance.

3.5. Time-dependent failure probability function (step 5)

According to previous sections, the failure probability of the AF-BA safety function could be understood as the sum of the contributions of a component associated with the probability to violate a critical MTC value (Section 3.3), and the one which represents the

Table 10
Probability of each AF-BA configuration.

		PZR PORVs RELIEF capacity									
		x8	x7	x6	x5	x4	x3	x2	x1	x0	
MDP-AFW	x4	9.07E-01	7.21E-03	1.19E-02	9.35E-05	5.10E-05	3.99E-07	3.17E-05	2.51E-07	1.44E-09	WITH TT
	x3	2.57E-02	2.23E-04	3.46E-04	2.89E-06	1.53E-06	1.23E-08	9.06E-07	7.73E-09	2.43E-10	
	x2	4.56E-02	3.65E-04	6.01E-04	4.74E-06	2.58E-06	2.02E-08	1.60E-06	1.27E-08	7.56E-11	
	x1	1.18E-03	1.02E-05	1.57E-05	1.31E-07	6.97E-08	5.60E-10	4.11E-08	3.52E-10	1.15E-11	
	x0	7.32E-05	5.94E-07	9.64E-07	7.71E-09	4.17E-09	3.29E-11	2.56E-09	2.06E-11	2.60E-13	
	x4	3.29E-04	2.62E-06	4.31E-06	3.40E-08	1.85E-08	1.45E-10	1.15E-08	9.10E-11	5.23E-13	WITHOUT TT
	x3	9.41E-06	8.09E-08	1.25E-07	1.05E-09	5.57E-10	4.47E-12	3.29E-10	2.81E-12	8.81E-14	
	x2	1.66E-05	1.32E-07	2.18E-07	1.72E-09	9.37E-10	7.33E-12	5.82E-10	4.60E-12	2.74E-14	
	x1	4.27E-07	3.68E-09	5.69E-09	4.77E-11	2.53E-11	2.03E-13	1.49E-11	1.27E-13	4.09E-15	
	x0	2.65E-08	2.16E-10	3.50E-10	2.18E-12	1.51E-12	1.15E-14	9.29E-13	7.33E-15	7.20E-17	

Table 11
Configuration probabilities and MCS of the AFW system.

	MDPs	Probability	Main MCS
AFW	4	9.26E-01	Default
	3	2.62E-02	Cooling unit failure MDP maintenance
	2	4.66E-02	TDP-Fail to run TDP-maintenance
	1	1.23E-03	Cooling unit failure of a MDP UMT and TDP-Fail to run
	0	7.55E-05	Operator fails to control the SGs level CST breakage

probability to have available a specific AF-BA configuration (Section 3.4). Therefore, the MC safety function could be implicitly considered within the assessment of the AF-BA performance, which justifies the decision to merge the described MC, AF, and BA safety functions in the same header, and its failure probability computed, providing a time-dependent probability function, as a result, see Fig. 22.

To compute the failure probability function of the AF+BA(t) header, the time-dependent SC functions computed in Section 3.3, Figs. 20 and 21, are used to identify the minimum AF-BA configurations able to successfully cope with the ATWS event at each particular time interval and, then, the probability to not have available those minimum configurations of AF-BA is calculated as the sum of the contributions of the failed configurations within that specific time interval computed employing the EET approach commented in Section 3.4, see Fig. 22.

For clarity's sake, the following example is included: if a success criterion for the AF and BA safety functions such as "1AFW + 1P3S or 2AFW + 0P3S" were considered, the probability of not having a successful configuration would be the sum of the range of values enlightened in bold in Table 13. As a result, the associated failure probability of the AF+BA(t) header is computed for the specific

Table 12
Configuration probabilities and MCS of PZR pressure relief system.

	Valves	Available	Probability	Main MCS
PZR	PORV	2	9.92E-01	Default
		1	7.90E-03	PZR-PORV fails to open
		0	5.14E-05	CCF wrong calibration of the PZR pressure channels PZR-PORV-A and B fail to open
	SVs	3	9.87E-01	Default
		2	1.27E-02	Wrong calibration of a PZR-SV PZR-SV fails to open
		1	5.45E-05	2 PZR-SVs calibration
		0	3.42E-05	CCF fail to calibrate the PZR-SVs CCF 3/3 PZR-SVs opening

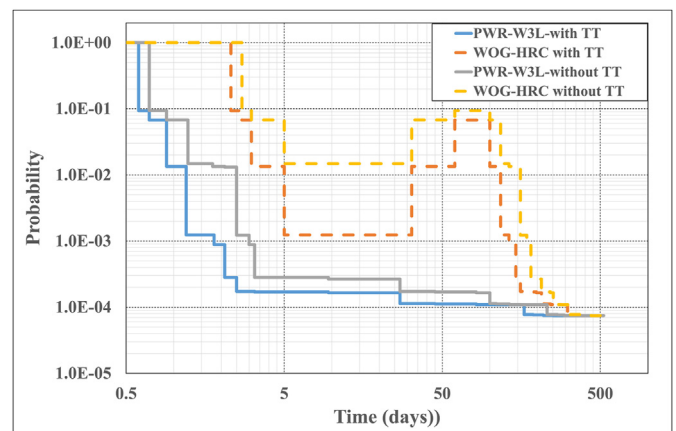


Fig. 22. Time-dependent failure probability of the AF+BA(t) header.

time interval during which that AF-BA configuration is the SC, see Fig. 22. Consequently, repeating that process for each possible SC obtained in Section 3.3, the time-dependent failure probability function of the AF+BA(t) across a fuel cycle calculation is performed.

3.6. Quantification of risk (step 6)

For the sake of a consistent comparison among the results, the classical ATWS ET described in Section 2.1 has been modified by adding a new AF+BA(t) header, representing the influence of MTC values along the cycle, and removing the SF header because of the results presented in section 2.4.2, see Fig. 23. Besides, the reader could realize that the order of the ET headers is not maintained with respect to the classical ATWS ET. In this case, the ET headers have been re-arranged to have the least number of sequences avoiding duplications.

Table 13
Failed configurations for the SC 1AFW + 1P3S OR 2AFW + 0P3S (in bold).

		PZR PORVs Relief capacity								
		x8	x7	x6	x5	x4	x3	x2	x1	x0
MDP-AFW	x4	9.07E-01	7.21E-03	1.19E-02	9.35E-05	5.10E-05	3.99E-07	3.17E-05	2.51E-07	1.44E-09
	x3	2.57E-02	2.23E-04	3.46E-04	2.89E-06	1.53E-06	1.23E-08	9.06E-07	7.73E-09	2.43E-10
	x2	4.56E-02	3.65E-04	6.01E-04	4.74E-06	2.58E-06	2.02E-08	1.60E-06	1.27E-08	7.56E-11
	x1	1.18E-03	1.02E-05	1.57E-05	1.31E-07	6.97E-08	5.60E-10	4.11E-08	3.52E-10	1.15E-11
	x0	7.32E-05	5.94E-07	9.64E-07	7.71E-09	4.17E-09	3.29E-11	2.56E-09	2.06E-11	2.60E-13

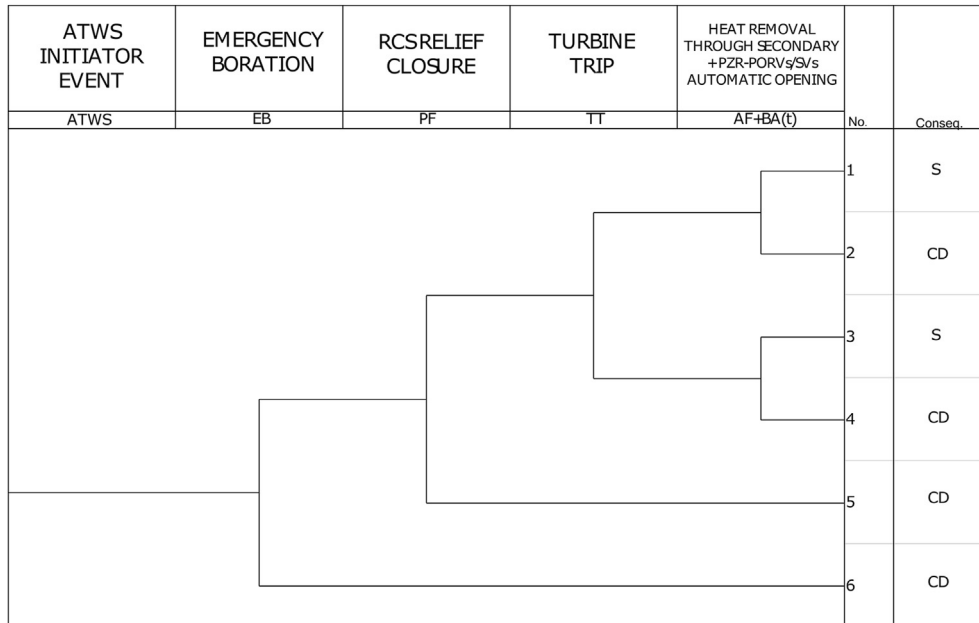


Fig. 23. ATWS ET associated with the time-dependent SC approach.

Table 14
Probability of failure of ATWS ET headers (time-dependent SC approach).

Header	Description	Success criteria	Probability to fail
EB	Emergency Boration	1/2 HPSI pump injecting to 1/3 CLs	5.81E-04
PF	PZR-PORVs/SVs Closure	PZR-PORVs/SVs closure	3.40E-05
TT	Turbine Trip	TT must be achieved	3.63E-04
AF	Heat removal through the secondary side (AFWS performance)	Time dependent SC	PWR-W3L w TT → 1.21E-03 WOG-HRC w TT → 1.11E-02
+	+	See Figs. 20–22	
BA	PZR-PORVs/SVs Automatic Opening		PWR-W3L w/o TT → 1.48E-03 WOG-HRC w/o TT → 2.03E-02

Table 15
Core damage probability results obtained for the time-dependent SC approach.

SEQUENCE	ATWS	State of the headers				Time dependent SC approach		
						Conseq	CD probability	
							PWR-W3L	WOG-HRC
1	EB	PF	TT	AF+BA	SUCCESS			
2	EB	PF	TT	af+ba	CD	1.21E-03	1.11E-02	
3	EB	PF	tt	AF+BA	SUCCESS			
4	EB	PF	tt	af+ba	CD	5.37E-07	7.35E-06	
5	EB	pf	-	-	CD	3.40E-05	3.40E-05	
6	eb	-	-	-	CD	5.81E-04	5.81E-04	
TOTAL						1.83E-03	1.17E-02	

Table 16
Comparison among the results obtained using different approaches

Approach	CCDP	Reference
Classical PSA	2.16E-02	Table 6
Classical PSA with PWR-W3L MTC function	7.13E-03	Table 6
Classical PSA with WOG-HRC MTC function	2.79E-01	Table 6
Time-dependent SC with PWR-W3L MTC function	1.83E-03	Table 15
Time-dependent SC with WOG-HRC MTC function	1.17E-02	Table 15

The quantification of risk starts with the calculation of the integral along the whole fuel cycle of the failure probability functions of the AF+BA(t) header obtained in Section 3.5, see Fig. 22. Once the failure probability of the AF+BA(t) header is computed, the quantification process can be done as usual considering also the failure probabilities of the EB, TT, and PF headers, see Table 14, and the sequences in the new ET, see Fig. 23.

The results obtained through the application of the new time-dependent SC methodology based on the EET approach applied in this study are presented in Table 15. Table 16 summarizes the comparison of the CCDP obtained using the approaches described in this paper and introduces the best estimate value of the CCDP to the ATWS event occurrence, by using the time-dependent SC methodology. These CCDP values diminish approximately in one order of magnitude in comparison with the classical value for both time-dependent MTC functions, the ones defined as PWR-W3L and WOG-HRC, see Table 16.

The reader should note that the methodology applied to carry out the quantification of risk following this new approach is slightly different from that applied in the classical PSA analyses since the CCDP is computed by multiplying the top event failure probabilities of each ET, instead of linking the ET with the corresponding FTs (classical PSA approach). However, this simplification has no relevant impact on the results because the ATWS headers can be considered independent of each other.

4. Conclusions

The main conclusions drawn from this study are the following:

- A new approach based on expanded ETs and temporal evolution of success criteria has been successfully developed to evaluate the CCDP in a specific NPP under ATWS conditions.
- It is demonstrated that with the considered MTC evolutions (depending on each plant and reload configuration) it is not possible to deal with the LONF-ATWS consequences during the early stage of the cycle despite the full availability of the AF-BA (secondary feed and primary relief) capacity. In addition, the length of that unfavorable interval of time, the SC temporal evolution, and the final CCDP value are strongly affected by the MTC function applied.
- In this study, it is shown that the fact that different SC can coexist during a specific interval of time could create new lines of operator actions to mitigate the consequences of the accident. In addition, the CCDP is highly reduced because of having different alternatives of success criteria under certain periods within the fuel cycle.
- The new approach applied in this work allows quantifying the evolution of the core damage probability and the MCS during the whole fuel cycle under ATWS conditions.
- This new Risk-Informed Assessment Methodology allows obtaining a better estimation of CCDP ATWS sequences. A reduction in the CCDP of one order of magnitude can be achieved by the application of the new methodology presented in

this study. So, this approach could be useful in cases in which the CCDP obtained by using the classical PSA approach is too high.

- The methodology presented in this study should not be applied in a generic manner. A devoted analysis associated with the peculiarities in the design of each NPP should be performed.
- The comparison between the classical PSA approach and the new time-dependent approach allows for quantifying the impact of some of the hypotheses made in the classical approach.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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