ANALYSES OF AP1000® EXPANDED EVENT TREE SEQUENCES BASED ON BEST-ESTIMATE CALCULATIONS

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Abstract: The Westinghouse **AP1000®** reactor is an advanced design whose safety systems are based on natural mechanisms such as gravity or natural circulation, namely, they are passive safety systems. Because of the passive nature of the safety related systems and its dependency on small changes on certain variables (e.g. pressure), it is necessary to confirm that when core cooling is achieved, uncertainties are bounded. The thermal-hydraulic (T/H) uncertainty evaluation process performed by Westinghouse Electric Company (WEC) identified a set of low T/H margin by expanding probabilistic risk assessment (PRA) event trees. Expanded event trees contain more branches than classic event trees, including all possibilities for system actuation. Then detailed conservative computer codes were applied in order to analyze the bounding sequences that were significant to the core damage frequency and demonstrating that the T/H uncertainty was bounded. The UPM group has analyzed the low-margin sequences obtained by WEC with the best estimate computer code TRACE in order to verify the previous results and also to study the phenomenology of such sequences through a best estimate code. This paper presents the results obtained for the DVI line break case confirming that it does not exist damage in the bounding sequence selected for that case.

Keywords: AP1000, DVI line break, Expanded event tress, Focused PRA, Passive safety systems

1. INTRODUCTION

An exhaustive range of activities as part of the **AP1000/AP600** certification process were performed in order to provide confidence on design capabilities and especially on the performing and reliability of the passive safety system. Due to the limited operational experience of the passive safety systems the inherent uncertainties related with the use of such systems must be considered since small changes in any of the physical parameters involved in a system performance (pressure, temperature, etc) could lead to different conclusions on the success core cooling.

The PRA provides insights into any plant vulnerability, so that, as in a standard one, in **AP1000** PRA [1] an event tree is constructed for each initiating event category, in order to model the accident sequences that may result. In the same way, it is necessary to determine the minimum number of systems and components that are necessary to provide adequate core cooling, namely, to define safety systems success criteria. This non-negligible work requires of extensive thermal-hydraulic analyses in order to justify the success criteria used in each event tree.

In the **AP1000** such justification was addressed, in part, through analysis performed in the Deterministic Safety Analysis (DSA) as part of the Design Control Document (DCD) [2] but in sequences which involved Automatic Depressurization System (ADS) actuation, (e.g. small break LOCA) the DSA T/H analysis was not applicable due to the assumption of single failure in such analyses. This fact leads to the performance of a large number of simulations due to the multiple combinations between events and failure combinations. Such analysis is only acceptable if fast computer codes are used. Therefore, MAAP4 code was used for this purpose. This issue was a licensing problem since the NRC required a more detailed analysis in order to bound the potential T/H uncertainties associated to the use of best estimate assumptions in MAAP4 and the limited details in such code [3].

In order to cope with this issue, Westinghouse developed an approach to bound the T/H uncertainty in the **AP1000** PRA success criteria analysis, see references [3], [4], [5] and [6]. This approach must demonstrate that the sequences which have been considered as success sequence in PRA are bounded by T/H uncertainties, namely, the success criteria have been defined for enclosing a range of accident conditions with enough margin to core damage.

The main task of this process is the expansion of the event trees in order to take into account more possibilities for system performance than those which are considered in success criteria and thereafter to identify which sequences are worthy to perform exhaustive analysis. In the following a description of the process as well as the analysis performed by the Universidad Politecnica de Madrid (UPM) will be described.

2. THERMAL-HYDRAULIC UNCERTAINTY EVALUATION PROCESS

This process must demonstrate that the sequences which have been considered as success sequence in PRA are bounded by T/H uncertainties. For this purpose, low-margin risk-significant sequences must be determined and the main way for finding such sequences is to expand the event trees of Focused PRA [3]. The Focused PRA is a sensitivity study to the **AP1000** PRA which does not include active systems for accident mitigation. The event-tree expansion of the Focused PRA contributes to distinguish the failed equipment from the functioning equipment since by expanding the trees, all the possibilities and not only success criteria are considered. Figure 1 shows an example of event tree expansion. For instance, the Core Makeup Tank (CMT) actuation possibilities are 1 out of 2 (success criteria) or zero while in the expanded tree also the possibility of 2 CMT actuation is taken into account.

Once the expansion of the event trees has been completed, the success sequences are grouped into two categories.

- OK category which contains success sequences in which the core remains covered during the whole transient
- UC category which contains success sequences in which some core uncovery is detected (low margin).

The success sequences with UC end states are conservatively considered to lead to core damage in order to allow quantification of their risk importance and are collected and ranked by their contributions to core damage frequency CDF and large release frequency (LRF), as shown in Table 1 (only the first 25 sequences have been collected for this paper. After that, only the sequences which contribute to the CDF or LRF with more than 1% of the base CDF or LRF are considered risk important. Being the base **AP1000** CDF and LRF frequencies 2.41E-07/year and 1.95E-08/year, respectively [1]. So that Westinghouse identified the 13 sequences which are gathered in Table 2.

Subsequently, the 13 risk important sequences are bounded by 5 short-term and 2 long-term sequences, see Tables 2 and 3. The final step of the process is to analyze such sequences by using DSA T/H computer codes (e.g. NOTRUMP) and methods to show if adequate core cooling is achieved and therefore T/H uncertainties are bounded. A schematic view of the whole T/H uncertainty evaluation process is shown in Figure 2.

Figure 1: Event tree expansion process

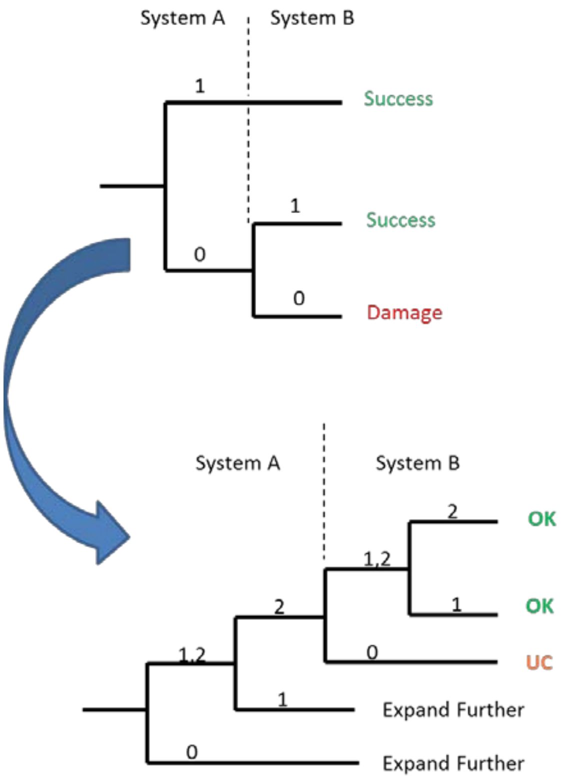


Table 1: PRA sequences sorted by CFD and LRF

Low Margin sequences sorted by potential core damage frequency												
Number	Initiating Event	Sequence CDF	Sequence LRF	Percentage CDF	Percentage LRF	CI	IRWST & RECIRC	CMT	ACCUM	ADS-4	ADS 2,3	BOUNDED By
1	SILB	8.96E-07	5.37E-08	371.66	275.6	Yes	Yes	1	0	4	2-4	C
2	SADS	4.58E-07	2.75E-08	190.05	140.93	Yes	Yes	2	1	4	2-4	E
3	SILB	3.05E-07	1.83E-08	126.76	94	Yes	Yes	0	1	4	2-4	A
4	MLOCA	2.89E-07	1.73E-08	119.85	88.88	Yes	Yes	0	2	4	2-4	AB
5	CMT	1.34E-07	8.05E-09	55.67	41.28	Yes	Yes	0	2	4	2-4	AB
6	SADS	9.12E-08	5.47E-09	37.82	28.05	No	Yes	2	2	4	2-4	E
7	MLOCA	3.01E-08	1.81E-09	12.48	9.26	Yes	Yes	2	0	4	2-4	C
8	LLOCA	8.51E-09	8,SIE-09	3.53	43.63	No	Yes	2	2	4	2-4	D
9	CMT	6.42E-09	3.85E-10	2.67	1.98	Yes	Yes	1	0	4	2-4	C
10	MLOCA	2.44E-09	1.47E-10	1.01	0.75	Yes	Yes	0	1	4	2-4	A
11	SILB	2.09E-09	1.25E-10	0.87	0.64	Yes	Yes	1	0	3	2-4	C
12	SILB	1.64E-09	9.83E-10	0.68	0.5	Yes	Yes	l	0	4	0-l	C
13	SILB	1.52E-09	1.52E-09	0.63	7.77	No	Yes	1	0	4	2-4	C
14	CMT	1.14E-09	6.85E-11	0.47	0.35	Yes	Yes	0	1	4	2-4	A
15	SADS	1.07E-09	6.42E-11	0.44	0.33	Yes	Yes	2	1	3	2-4	
16	SADS	8.40E-10	5.04E-11	0.35	0.26	Yes	Yes	2	1	4	0-1	E
17	SADS	7.77E-10	4.66E-11	0.32	0.24	No	Yes	2	1	4	2-4	E
18	SILB	7.21E-10	4.32E-11	0.3	0.22	Yes	Yes	0	1	3	2-4	
19	MLOCA	6.92E-10	4.15E-11	0.29	0.21	Yes	Yes	0	2	3	2-4	
20	SADS	6.76E-10	4,05E-1l	0.28	0.21	Yes	Yes	1	1	4	2-4	E
21	MLOCA	6.44E-10	3.86E-11	0.27	0.2	Yes	Yes	0	2	4	0-1	AB
22	SILB	6.15E-10	3.69E-11	0.26	0.19	Yes	Yes	0	1	4	0-1	A
23	SILB	5.16E-10	5.16E-10	0.21	2.65	No	Yes	0	1	4	2-4	A
24	MLOCA	4.88E-10	4.88E-10	0.2	2.5	No	Yes	0	2	4	2-4	A
25	CMT	3.17E-10	1.90E-11	0.13	0.1	Yes	Yes	0	2	3	2-4	

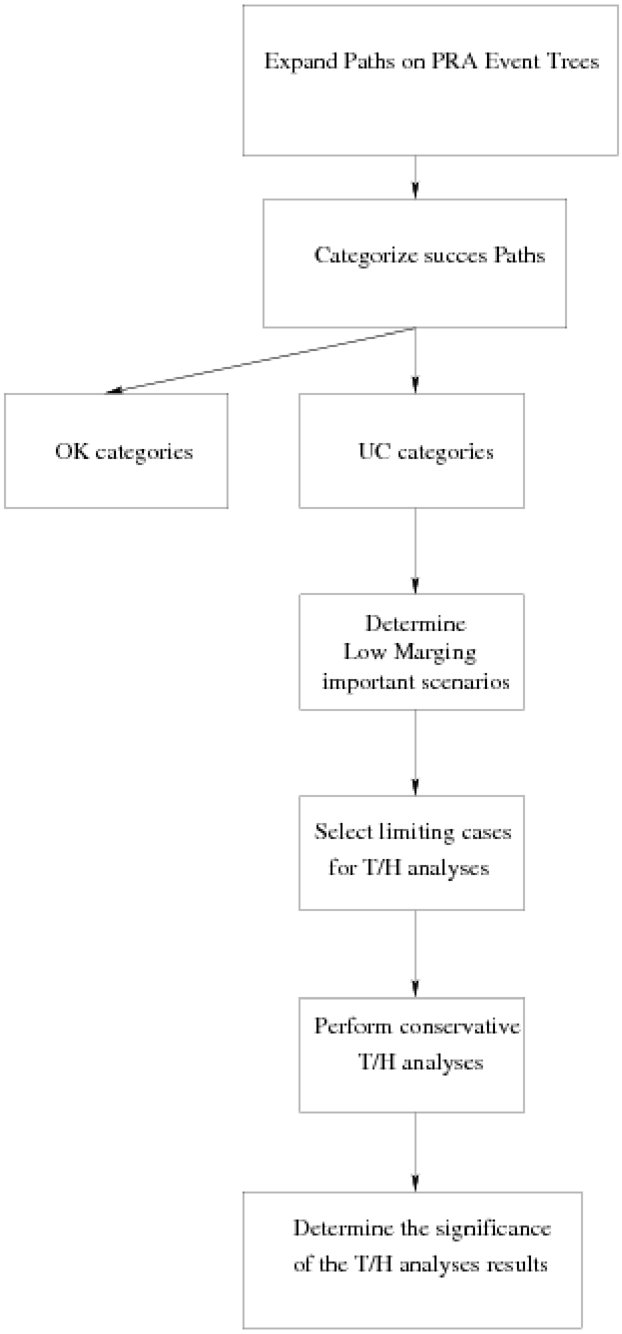
Table 2: PRA risk important sequence

AP1000 Thermal-Hydraulic Uncertainty Low Margin/Risk Important sequences													
Case/LM	**Initiating event**	**CI**	**IRWST & RECIRC**	**CMT**	**ACC**	**ADS-4**	**ADS 2/3**	**PRHR**	**CDF**	**LRF**	**%CDF**	**%LRF**	**Bounding sequence**
1	SILB	Yes	Yes	1	0	4	02-abr	N/A	8.96E-07	5.37E-08	317.7	275.6	C
2	SADS	Yes	Yes	2	1	4	2-4	N/A	4.58E-07	2.75E-08	190.1	140.9	E
3	SILB	Yes	Yes	0	1	4	2-4	Yes	3.05E-07	1.83E-08	126.8	94	A
4	MLOCA	Yes	Yes	0	2	4	2-4	Yes	2.89E-07	1.73E-08	119.9	88.9	B
5	CMT	Yes	Yes	0	2	4	2-4	Yes	1.34E-07	8.05E-09	55.7	41.3	B
6	SADS	No	Yes	2	2	4	2-4	N/A	9.12E-08	5.47E-09	37.8	28	E
7	MLOCA	Yes	Yes	2	0	4	2-4	N/A	3.01E-08	1.81E-09	12.5	9.3	C
8	LLOCA	No	Yes	2	2	4	2-4	N/A	8.51E-09	8.51E-09	3.5	43.6	D
9	CMT	Yes	Yes	1	0	4	2-4	N/A	6.42E-09	3.85E-10	2.7	2	C
10	MLOCA	Yes	Yes	0	1	4	2-4	Yes	2.44E-09	1.47E-10	l,0	0.8	A
11	SJLB	No	Yes	1	0	4	2-4	N/A	1.52E-09	1.52E-09	0.6	7.8	C
12	SILB	No	Yes	0	1	4	2-4	Yes	5.16E-10	5.16E-10	0.2	2.6	A
13	MLOCA	No	Yes	0	2	4	2-4	Yes	4.88E-10	4.88E-10	0.2	2.5	A
							Totals =		2.22E-06	1.44E-07			

Table 3: Low margin bounding sequences (WEC results)

Bounding Sequences Analyzed for T/H Uncertainty									
Analysis case	**Initiating event**	**Cont. Isol**	**IRWST & RECIRC**	**CMT**	**ACC**	**ADS-4**	**PRHR HX**	**Bounds Risk Important Case**	**Core Peak Clad Temp**
Short-term Cooling									
A	Reactor coolant system hot leg (3.0")	No	Yes	0	1	4	Yes	3,10,12,13	No uncovery
B	Double-ended CMT balance line (6.8")	Yes	Yes	0	2	4	Yes	4.5	No uncovery
C	Double-ended DVI line (4")	No	Yes	1	0	3	No	1,7,9,11	1127 K
D	Double-ended cold-leg LLOCA	No	Yes	2	2	4	Yes	8	1288 K
E	Spurious ADS-4	No	Yes	1	1	4	Yes	2.6	844 K
Long-term Cooling									
F	Double-ended DVI line (4")	Yes	1/1&1/1	1	0	3	No	1-5,7,9,10	No uncovery
G	Double-ended DVI line (4")	No	1/1&1/2	1	0	4	No	6,8,11-13	No uncovery

Figure 2: T/H uncertainty evaluation process



3. ANALYSES OF AP1000 LOW MARGIN SEQUENCES BASED ON BEST ESTIMATE CALCULATIONS

As described in the previous section, once the low margin risk important sequences have been identified, detailed DCD computer codes and assumptions are used to evaluate these sequences and to demonstrate that T/H uncertainties are bounded. As shown in Table 3, five short-term bounding sequences and two long-term bounding sequences were determined [4]. The results obtained by Westinghouse (last column of table) shows that only three out of the seven sequences present core uncovery but they do not exceed Peak Cladding Temperature (PCT) limit in any case.

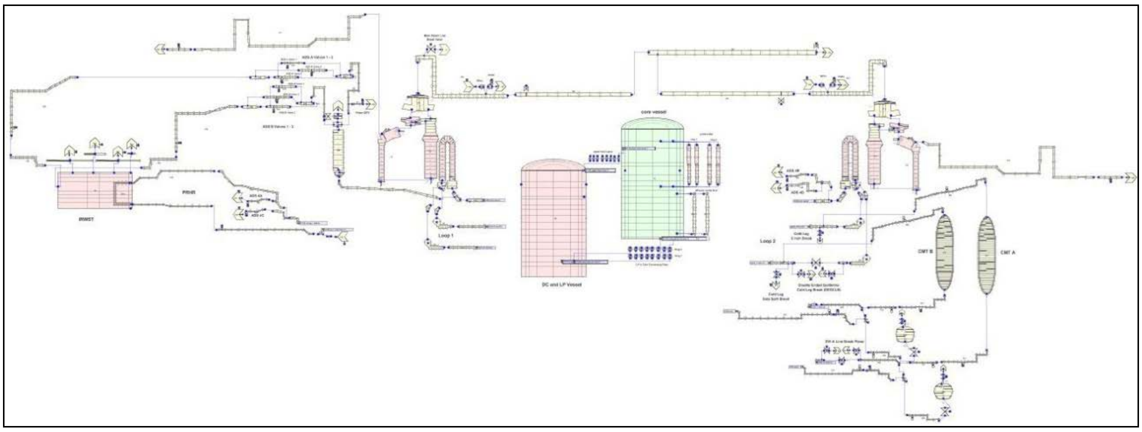
The bounding sequence "C" is especially important since the direct vessel injection (DVI) line break initiating event has been categorized as the even with the largest contribution to CDF in AP1000 PRA accounting for 39.4% of the total [1]. Moreover, this sequence bounds the low margin sequence with largest contribution to CDF and LRF being 317% and 275,6% respectively, see Table 2. The analysis performed with NOTRUMP predicts for this bounding sequence a PCT of 1127K, Table 3. This particular sequence presents the following systems availability for the accident mitigation: 1 CMT, 3 out of 4 ADS stage-4 valves and IRWST injection.

The UPM group has analyzed the DVI short-term low-margin risk-important sequence with the best estimate TRACE code in order to compare the results obtained with a detailed DCD conservative code against a more realistic analysis.

The AP1000 model for TRACE code V 5.0 patch 2, [8] used in the analysis consists of all the main components such as vessel, Steam Generators, Pressurizer, Reactor Coolant Pumps (RCPs) and connecting pipes as well as the passive safety systems, Core Makeup Tanks (CMTs), Accumulators (ACCs), Automatic Depressurization System (ADS), Passive Residual Heat Removal system (PRHR). No active systems are implemented in this model.

The total number of thermal hydraulic components presented in the **AP1000** TRACE model is 368, being 86 PIPEs 191 HTSTRs, 3 POWERs, 44 VALVEs, 4 PUMPs, 24 BREAKs, 10 TEEs, 3 FILLs and 3 VESSELs. In addition 119 TRIPS, 377 CONTROL BLOCKS and 447 SIGNAL VARIABLES complete the model, see Figure 3.

Figure 3: AP1000 TRACE model in SNAP nodalization



4. DIRECT VESSEL INJECTION LINE BREAK SEQUENCE EVOLUTION

The size of the DVI line is 6.8 inches but the inlet nozzle (vessel side) presents a 4-inch flow restrictor which limits the effective break size and hence the maximum flow that can be depleted through the break. Accordingly, the event is classified as a medium LOCA.

An important difference respect to other MBLOCAs (hot leg and cold leg) is that, in this kind of sequence, 1 CMT, 1 ACC and 1 IRWST injection line became unavailable due to the location of the break. In addition, since the outlet of the normal residual heat removal system (active system) is connected to both DVI, it is also assumed that the water from this system is lost through the broken line [1].

As in a standard LOCA, the event results in a reactor trip and safety injection signal “S” that causes RCP trip and CMT actuation. The ADS-1 actuates after CMT low level signal (67%) and the accumulators should inject when the pressure is lower than 49 bar. When a full depressurization has been achieved, the IRWST begin to drain into the reactor. The main setpoints involved in this kind of sequence are listed in Table 4 [2].

It must be pointed out that the DVI sequence which is simulated in this analysis (bounding sequence "C" of T/H uncertainty evaluation process) is not a typical LOCA sequence but presents some restrictions, which are the following ones: 1 CMT is available, both accumulators are not able to inject, the ADS stages 1, 2 and 3 do not actuate neither and the full depressurization is achieved only with 3 out of 4 valves of ADS stage 4 whose setpoint is reached when the level in the available CMT is 20%. Thereafter the low pressure injection is achieved through the IRWST. Moreover, the PRHR is not credited since it is not a part of success criteria in sequences with automatic ADS leading to IRWST gravity injection [5], see Table 3 case "C".

Table 4: Main setpoints for tipycal DVILB sequence. (*) unavailable system for the analyzed bounding sequence "C".

Function	Setpoints assumed in DVILB analysis
Reactor trip on low pressurizer pressure	124 bar
"S" signal on low-low pressurizer pressure	117 bar
Reactor coolant pumps trip	"S" signal + 6 sec
PRHRS valve starts to open (*)	"S" signal
CMT injection starts (1 out of 2)	"S" signal + 2 sec
ACC injection starts on low RCS pressure (*)	49bar
ADS-1 (*)	Low CMT level (67.5%)
ADS-2,3 (*)	Delay with respect ADS-1
ADS-4 (3 out of 4)	Low-Low CMT level (20%)
IRWST valve opens	ADS-4 actuation

5. ANALISIS OF LOW MARGIN DVI RISK IMPORTANT SEQUENCE WITH TRACE CODE.

This section presents the simulation performed with TRACE code for DVI line break low-margin sequence. As described before, the system availability of this sequence is as follows: 1 out of 2 CMT (intact loop), 0 out of 2 ACC, stages 1, 2 and 3 of the ADS do not actuate, 3 out of 4 ADS stage 4 valves and IRWST injection. Figure 4, shows the AP1000 RCS with availability of systems in this sequence. The results are plotted comparing with those obtained with NOTRUMP by Westinghouse [4]. The chronology of the sequence is presented in Table 5.

As it is depicted in Figure 5, the pressure decrease (blowdown phase) presents a similar trend in both cases until the pressure stabilizes below 100 bar. After that, TRACE predicts a longer stabilization at the secondary pressure.

In this sequence there is not core cooling through the Passive Residual Heat Removal (PRHR) system and therefore the available CMT is the only way to cool the core until the ADS stage 4 allows the actuation of the IRWST. Although the CMT flow predicted by TRACE is slightly greater Figure 6, the trend is quite similar. The time when the CMT reach the 20% of its level and therefore the ADS stage 4 actuates, is appreciable in both cases since the flow rate is increased at this time. This moment is also appreciable in the pressure plot where a depressurization step between about 25 bar and containment pressure is achieved very quickly.

Later, when the IRWST injection is achieved, the system is again pressurized above the IRWST injection pressure, which produces a short interruption in the flow rate, Figure 7. The minimum core level is reached at about 1900 seconds producing a fast rise in the clad temperature. When the water from the IRWST flows into the system the core level is recovered and the temperatures remain low. It is appreciable that the PCT value obtained in the analysis performed with NOTRUMP for this sequence (1127 K), see Table 3, is higher than the obtained with TRACE code (600 K), Figure 8. It must be taken into account that NOTRUMP analysis includes more conservative models and assumptions than TRACE

Figure 4: DVILB low magin sequence. Availability emergency systems

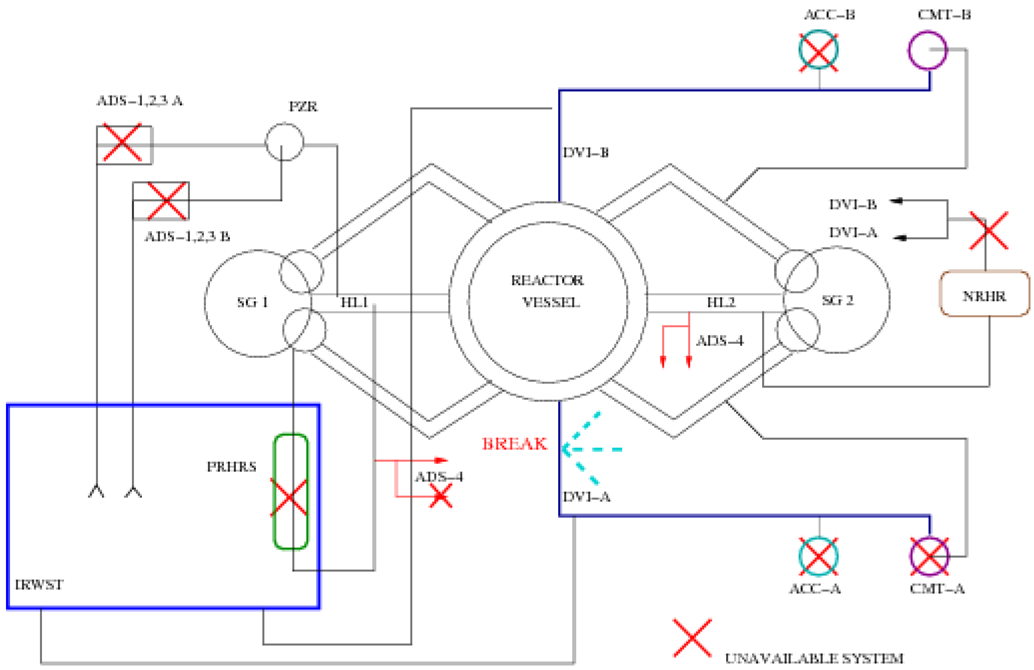


Table 5: DVI line break low margin sequence chronology. TRACE code.

Event	Time (s)
Break opens	0
Reactor trip	24.3
"S" signal	27.2
RCP trip	33.2
CMT injection starts	39.2
Auto ADS-4	1355
IRWST injection	1870.3
Maximum PCT	1995.1

Figure 5: DVILB low magin sequence. Pressure transient. TRACE vs NOTRUMP

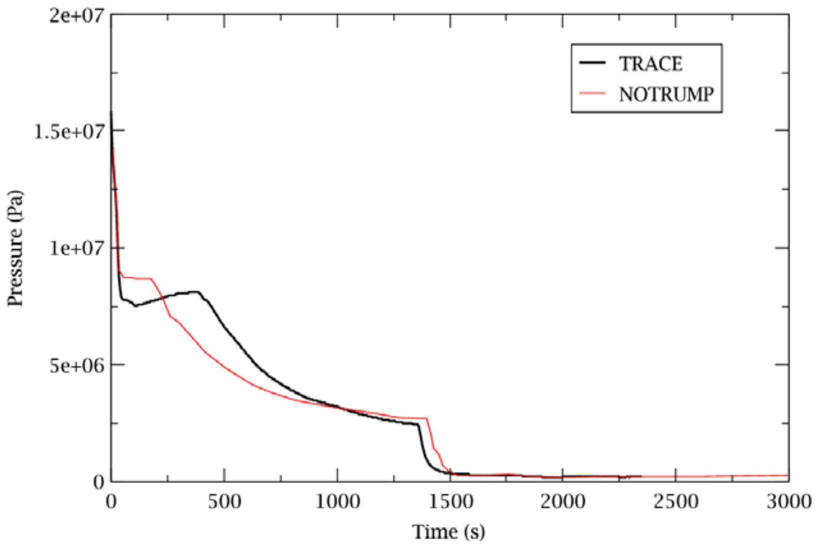


Figure 6: DVILB low magin sequence. CMT injection flow rate. TRACE vs NOTRUMP

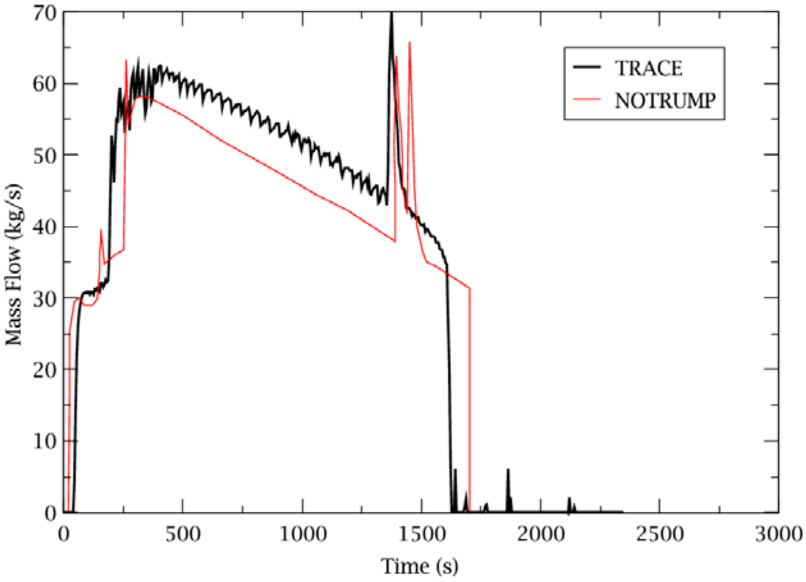


Figure 7: DVILB low magin sequence. IRWST injection flow rate. TRACE vs NOTRUMP

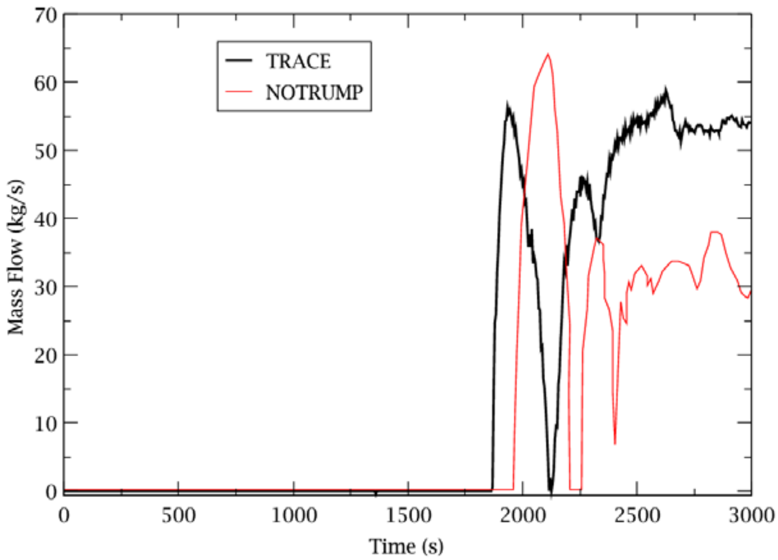
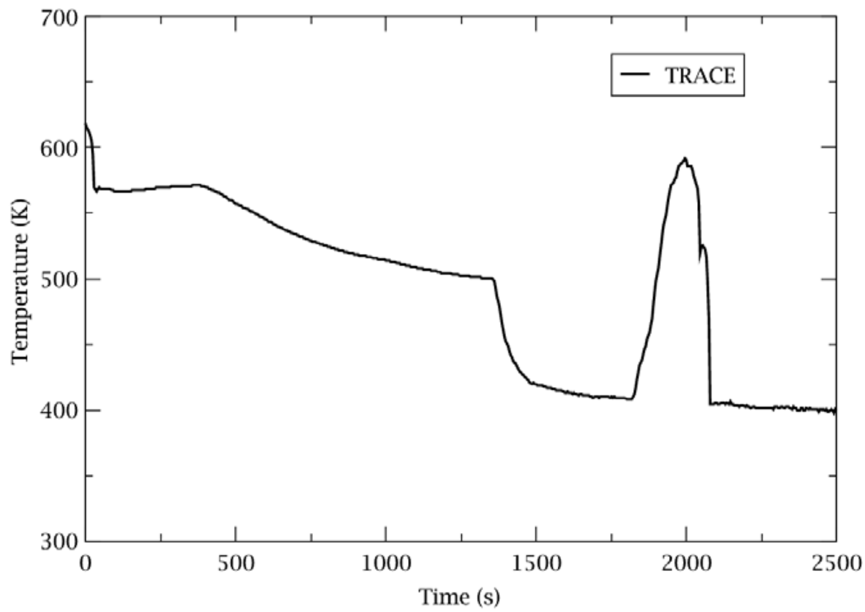


Figure 8: DVILB low magin sequence. Peak cladding temperature. TRACE



6. CONCLUSIONS

This paper sumarizes the thermal hydraulic uncertainty evaluation process developed by Westinghouse in order to bound the possible uncertainties that can affect to the PRA succes criteria due to the use of passive safety systems in **AP1000** reactor.

The UPM group has analyzed the DVILB low margin sequence with the best estimate TRACE computer code in order to verify how the behaviour of the plant would be in a more realistic case. The results show a very similar trend between TRACE and NOTRUMP simulations, but the PCT value obtained with TRACE remain well below as the predicted by NOTRUMP. The result is the expected since, the NOTRUMP code is the DSA computer code used by WEC for SBLOCA analysis.

This result has allowed to verify and confirm the **AP1000** thermal-hydraulic uncertaintiy evaluation process peformed by WEC for the most risk-important low-margin sequence

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DISCLAIMER

This paper is the result of the analysis carried out by the research group of the Technical University of Madrid and therefore Westinghouse Electric Company and the USNRC were not involved in such investigations and they are not responsible about the contents here exposed.