Verification of **AP1000**[®] low-margin PRA sequences based on best-estimate calculations

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A B S T R A C T

The Westinghouse **AP1000**[®] reactor is an advanced design whose safety systems are mainly passive safety systems. Due to the passive nature of the safety related systems and its dependency on small changes on certain variables (e.g. pressure, friction coefficients) together with the use of a simplified code like MAAP in Probabilistic Risk Assessment (PRA) analyses, it makes necessary to confirm that when core cooling is achieved, thermal-hydraulic (T/H) uncertainties are bounded. The T/H uncertainty evaluation process performed by Westinghouse Electric Company (WEC) identified the low-margin sequences (core uncover) by expanding PRA Event Trees (ETs). The expanded ETs allowed finding the low-margin risk-important sequences and then a set of low-margin bounding sequences was selected. Then detailed safety analysis methodologies were applied in order to evaluate the bounding sequences demonstrating that the T/H uncertainties were bounded. The Universidad Politécnica de Madrid group has verified the low-margin bounding sequences obtained by WEC with the best-estimate TRACE code 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 short-term low-margin bounding sequences. In general, TRACE results do not present important discrepancies with respect to NOTRUMP and WCOBRA/TRAC results although TRACE presents lower values for Peak Cladding Temperature. This analysis has allowed to verify the **AP1000** thermal-hydraulic bounding evaluation process performed by WEC for the low-margin risk-important sequences with TRACE code.

1. Introduction

The success criteria justification in the **AP1000** Probabilistic Risk Assessment (PRA) was addressed, in part, through the analysis performed in the Deterministic Safety Analysis (DSA) as part of the Design Control Document (DCD) (Westinghouse Electric Company, 2008) but in sequences which involved Automatic Depressurization System (ADS) actuation, (e.g. small break LOCA) the DSA

Thermal-Hydraulic (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. These analyses are only feasible if fast computer codes are used. Therefore, MAAP4 code (MAAP4, 1994) was selected for this purpose, see (Westinghouse Electric Company, 2003b). 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 parameter values (e.g. residual heat) and the limited details and simplified TH models included in MAAP code (Selim Sancaktar and Terry Schulz, 2004).

In order to cope with this issue, Westinghouse Electric Company (WEC) developed an approach to bound the T/H uncertainty in the **AP600** PRA success criteria analysis which was also applied to the **AP1000**, see references (Selim Sancaktar and Terry Schulz, 2004; Ohkawa et al., 1997; Westinghouse Electric Company, 2003a; Advisory Committee on Reactor safeguards subcommittees on Reliability and probabilistic Risk Assessment, 2003). This approach must demonstrate that the low margin

Abbreviations: ACC, Accumulator; ADS, Automatic Depressurization System; BE, Best-Estimate; BS, Bounding Sequence; CDF, Core Damage Frequency; CMT, Core Make-up Tank; DSA, Deterministic Safety Analysis; DVI, Direct Vessel Injection; DVLB, Direct Vessel Injection Line Break; EET, Expanded Event Tree; ET, Event Tree; IAEA, International Atomic Energy Agency; IRWST, In Containment Refueling Water Storage Tank; LM, Low Margin sequence; LOCA, Loss of Coolant Accident; LRF, Large Release Frequency; NRC, Nuclear Regulatory Commission; PCT, Peak Cladding Temperature; PRA, Probabilistic Risk Assessment; PRHR, Passive Residual Heat Removal; PWR, Pressurized Water Reactor; PZR, Pressurizer; RCS, Reactor Coolant System; SSG, Specific Safety Guide; T/H, Thermal Hydraulic; WEC, Westinghouse Electric Company.

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sequences (core uncover sequences) which have been considered as success sequences in PRA are bounded by T/H uncertainties.

The methodology developed by WEC identified the low-margin sequences by expanding PRA Event Trees (ET). The expanded ETs allowed to find the low-margin risk-important sequences and then a set of low-margin bounding sequences was selected. Then detailed safety analysis methodologies were applied in order to evaluate the bounding sequences. Several DSA methodologies corresponding to different options of the IAEA Specific Safety Guide SSG-2, see Table 1 and (IAEA, 2009), were applied by WEC to evaluate each low-margin bounding sequence.

The main goal of this work is to reproduce and verify the whole bounding process proposed by WEC including the simulation of all short-term low-margin bounding sequences applying the SSG-2 option 2 methodology.

This work has been developed in the frame of the “Integrated Safety Analysis Methodology Applied to Advanced Reactors (ISAMAR)” project. The ISAMAR project includes several DSA and PRA verifications like LBLOCA-BEPU (DSA), SBLOCA (DSA), Direct Vessel Injection Line Break (DVILB) ET delineation (PRA) and available time in DVILB sequences, see (Montero-Mayorga et al., 2015, 2014; Queral et al., 2015; Queral and Montero-Mayorga, 2016).

In the sequel, Section 2 presents the **AP1000** passive safety systems. Section 3 provides a description of low-margin sequences evaluation process. Section 4 gives an overview about LOCA sequences in the **AP1000** reactor and the **AP1000** TRACE model nodalization is presented in Section 5. The analysis of low-margin bounding sequences as well as main results obtained is presented in Section 6. Finally, Section 7 collects the main conclusions of this paper.

2. AP1000 passive safety systems

Basically, the same configuration of typical PWRs safety systems is used for **AP1000**, one system for high pressure safety injection (CMTs), one system for medium pressure safety injection (accumulators) and one system for low pressure safety injection (IRWST). However, these systems are significantly simpler than typical PWR safety systems since they contain significantly fewer components. In addition a new system for passive core cooling is implemented (PRHR) as well as one system for ADS. Figs. 1 and 2 show a schematic view of **AP1000** reactor and the main systems. The **AP1000** passive safety systems are briefly described below (Westinghouse Electric Company, 2008):

- *Core Makeup Tanks (CMTs)*. There are two CMTs as part of the passive safety system in **AP1000**. These tanks are cylindrical with an hemispherical upper and lower head. The CMTs are located above the Direct Vessel Injection (DVI), Fig. 1, and they are filled with cold (≈ 320 K) borated water at the Reactor Coolant System (RCS) pressure. Each tank (70.8 m^3) is connected to one cold leg of the same loop from the upper part and to the DVI

from the lower part. In normal operation the balance line (connection from the RCS to the upper part of the CMT) is normally open. However, the discharge of the CMTs is isolated upon receipt a safeguards signal **S**. In case of demand, the CMTs can operate in two different ways, injection and recirculation modes.

- *Accumulators (ACCs)*. As in a standard PWR the **AP1000** includes ACCs as well. There are 2 spherical ACCs (57 m^3 each) located just below the CMTs and are filled with borated water (≈ 320 K) and pressurized with nitrogen (49 bar). Like the CMTs, the ACCs are connected to the DVI lines. In normal operation the ACCs are isolated by check valves. If the RCS pressure falls below the ACCs pressure, the check valves open. The ACCs are necessary in order to reflood the core in case of LOCA providing borated water at high flow.
- *In Containment Refueling Water Storage Tank (IRWST)*. The IRWST is a large tank (2070 m^3) located inside the containment and above the RCS. Two lines connect the lower part of the IRWST with both DVI lines. The borated water (≈ 320 K) inside the IRWST will drain by gravity into the RCS when the pressure is close to the containment pressure.
- *Passive Residual Heat Removal System (PRHR)*. The passive core cooling system includes a PRHR heat exchanger located inside the IRWST. The inlet of the system is connected to one of the hot legs at and the outlet is connected to the corresponding steam generator water box. The IRWST provides the heat sink for the PRHR with a water volume sufficient to absorb decay heat for more than one hour before the water begins to boil.
- *Automatic Depressurization System (ADS)*. The ADS consists of four valves stages. It can be differentiated between the three first stages and the fourth one. Stages 1/2/3 (ADS-1/2/3) consist of two lines each. Such lines are included as part of the PZR safety and relief valve module being connected to the top of the PZR. The discharge of these valves is located inside the IRWST. On the other hand, stage-4 (ADS-4) has four lines connected to the hot legs which discharges directly to the containment. The whole system accounts for a total of 20 valves: ADS-1 is composed by 4-inch motor-operated valves, ADS-2/3 are 8-inch motor-operated valves and ADS-4 is composed by 14-inch squib valves.

3. Low-margin sequences evaluation process

This section describes the methodology followed by WEC to identify low-margin sequences (sequences with core uncover) and thereafter, how such sequences are evaluated. This process must demonstrate that the low margin sequences which have been considered as success sequences in PRA are bounded by T/H uncertainties. For this purpose, low-margin risk-important sequences must be determined and verified by means of thermal hydraulic analysis. The main steps of the WEC methodology are the following (Westinghouse Electric Company, 2003a), Fig. 3:

1. To delineate the Focused PRA (Selim Sancaktar and Terry Schulz, 2004). The Focused PRA is a sensitivity study of the **AP1000** PRA which does not include active systems like the Normal Residual Heat Removal System for accident mitigation.
2. To expand the ETs of the Focused PRA. The expanded event trees (EET) include all the possible systems configuration and not only success criteria configurations are considered. For instance, the CMTs actuation possibilities in the standard ET are 1 out of 2 (success criteria) or zero, while in the EET the possibility of 2 out of 2 CMT actuation is also taken into account.

Table 1
Options for DSA methodologies, IAEA Specific Safety Guide SSG-2, (IAEA, 2009).

Option	Computer code	Availability of systems	Initial and boundary conditions
1	Conservative	Conservative assumptions	Conservative input data
2	BE	Conservative assumptions	Conservative input data
3	BE	Conservative assumptions	Realistic input data with uncertainties
4	BE	Probabilistic safety analysis based assumptions	Realistic input data with uncertainties

Fig. 1. AP1000 Elevation view.

Fig. 2. AP1000 Plant view.

3. Once the expansion of the ET has been completed, the success sequences are binned 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 uncover is detected (low-margin sequences).
4. The low-margin sequences are conservatively considered to lead to core damage in order to allow quantification of their

Fig. 3. Low-Margin Sequences Evaluation Process.

risk importance and are collected and ranked by their potential contributions to Core Damage Frequency (CDF) and Large Release Frequency (LRF), as shown in Table 2 (only the first 25 sequences have been collected for this paper from (Westinghouse Electric Company, 2003a), DFi sequences).

- Only those sequences which can potentially contribute to the CDF or LRF with more than 1% of the base CDF or LRF are considered as low-margin risk-important sequences (LMi sequences), being the base CDF and LRF $2.41\text{E-}07/\text{year}$ and

$1.95\text{E-}08/\text{year}$, respectively (Westinghouse Electric Company, 2003b). WEC identified thirteen low-margin risk-important sequences which are gathered in Table 3. It is important to remark that all these sequences correspond to different kinds of LOCA sequences. These low-margin risk-important sequences have the following characteristics in common (Westinghouse Electric Company, 2003a): 4 out of 4 ADS-4 valves and several of ADS-2/3 valves available; Six sequences have one tank (CMT or ACC) available; the remaining sequences

Table 2

PRA low-margin sequences sorted by potential CDF and LRF (DFi sequences) (Westinghouse Electric Company, 2003a).

DFi Sequence	Initiating Event	Sequence CDF	Sequence LRF	Percentage CDF	Percentage LRF	CI	IRWST & RECIRC	CMT	ACC	ADS-4	ADS-2/3	Bounding Sequences
DF1	DVILB	8.96E-07	5.37E-08	371.66	275.6	Yes	Yes	1	0	4	2-4	BS-C
DF2	SADS	4.58E-07	2.75E-08	190.05	140.93	Yes	Yes	2	1	4	2-4	BS-E
DF3	DVILB	3.05E-07	1.83E-08	126.76	94	Yes	Yes	0	1	4	2-4	BS-A
DF4	MBLOCA	2.89E-07	1.73E-08	119.85	88.88	Yes	Yes	0	2	4	2-4	BS-A, BS-B
DF5	CMT	1.34E-07	8.05E-09	55.67	41.28	Yes	Yes	0	2	4	2-4	BS-A, BS-B
DF6	SADS	9.12E-08	5.47E-09	37.82	28.05	No	Yes	2	2	4	2-4	BS-E
DF7	MBLOCA	3.01E-08	1.81E-09	12.48	9.26	Yes	Yes	2	0	4	2-4	BS-C
DF8	LBLOCA	8.51E-09	8.51E-09	3.53	43.63	No	Yes	2	2	4	2-4	BS-D
DF9	CMT	6.42E-09	3.85E-10	2.67	1.98	Yes	Yes	1	0	4	2-4	BS-C
DF10	MBLOCA	2.44E-09	1.47E-10	1.01	0.75	Yes	Yes	0	1	4	2-4	BS-A
DF11	DVILB	2.09E-09	1.25E-10	0.87	0.64	Yes	Yes	1	0	3	2-4	BS-C
DF12	DVILB	1.64E-09	9.83E-10	0.68	0.5	Yes	Yes	1	0	4	0-1	BS-C
DF13	DVILB	1.52E-09	1.52E-09	0.63	7.77	No	Yes	1	0	4	2-4	BS-C
DF14	CMT	1.14E-09	6.85E-11	0.47	0.35	Yes	Yes	0	1	4	2-4	BS-A
DF15	SADS	1.07E-09	6.42E-11	0.44	0.33	Yes	Yes	2	1	3	2-4	
DF16	SADS	8.40E-10	5.04E-11	0.35	0.26	Yes	Yes	2	1	4	0-1	BS-E
DF17	SADS	7.77E-10	4.66E-11	0.32	0.24	No	Yes	2	1	4	2-4	BS-E
DF18	DVILB	7.21E-10	4.32E-11	0.3	0.22	Yes	Yes	0	1	3	2-4	
DF19	MBLOCA	6.92E-10	4.15E-11	0.29	0.21	Yes	Yes	0	2	3	2-4	
DF20	SADS	6.76E-10	4.05E-11	0.28	0.21	Yes	Yes	1	1	4	2-4	BS-E
DF21	MBLOCA	6.44E-10	3.86E-11	0.27	0.2	Yes	Yes	0	2	4	0-1	BS-A, BS-B
DF22	DVILB	6.15E-10	3.69E-11	0.26	0.19	Yes	Yes	0	1	4	0-1	BS-A
DF23	DVILB	5.16E-10	5.16E-10	0.21	2.65	No	Yes	0	1	4	2-4	BS-A
DF24	MBLOCA	4.88E-10	4.88E-10	0.2	2.5	No	Yes	0	2	4	2-4	BS-A
DF25	CMT	3.17E-10	1.90E-11	0.13	0.1	Yes	Yes	0	2	3	2-4	

Table 3

PRA low-margin risk-important sequences (LMi) (Westinghouse Electric Company, 2003a).

LMi Sequence	Initiating event	CI	IRWST & RECIRC	CMT	ACC	ADS-4	ADS-2/3	PRHR	CDF	LRF	%CDF	%LRF	Bounding Sequence
LM1	DVILB	Yes	Yes	1	0	4	2-4	N/A	8.96E-07	5.37E-08	317.7	275.6	BS-C
LM2	SADS	Yes	Yes	2	1	4	2-4	N/A	4.58E-07	2.75E-08	190.1	140.9	BS-E
LM3	DVILB	Yes	Yes	0	1	4	2-4	Yes	3.05E-07	1.83E-08	126.8	94	BS-A
LM4	MBLOCA	Yes	Yes	0	2	4	2-4	Yes	2.89E-07	1.73E-08	119.9	88.9	BS-B
LM5	CMT	Yes	Yes	0	2	4	2-4	Yes	1.34E-07	8.05E-09	55.7	41.3	BS-B
LM6	SADS	No	Yes	2	2	4	2-4	N/A	9.12E-08	5.47E-09	37.8	28	BS-E
LM7	MBLOCA	Yes	Yes	2	0	4	2-4	N/A	3.01E-08	1.81E-09	12.5	9.3	BS-C
LM8	LBLOCA	No	Yes	2	2	4	2-4	N/A	8.51E-09	8.51E-09	3.5	43.6	BS-D
LM9	CMT	Yes	Yes	1	0	4	2-4	N/A	6.42E-09	3.85E-10	2.7	2	BS-C
LM10	MBLOCA	Yes	Yes	0	1	4	2-4	Yes	2.44E-09	1.47E-10	1.0	0.8	BS-A
LM11	DVILB	No	Yes	1	0	4	2-4	N/A	1.52E-09	1.52E-09	0.6	7.8	BS-C
LM12	DVILB	No	Yes	0	1	4	2-4	Yes	5.16E-10	5.16E-10	0.2	2.6	BS-A
LM13	MBLOCA	No	Yes	0	2	4	2-4	Yes	4.88E-10	4.88E-10	0.2	2.5	BS-A
Total =									2.22E-06	1.44E-07			

have two to four tanks (both ACCs and CMTs) available, The sequences without CMTs have the PRHR available (PRA success criteria).

- Subsequently, five short-term and two long-term bounding sequences (BS-k) were selected by WEC to be analysed to bound the risk-important low-margin sequences, as shown in Table 4. None BS-k sequence includes ADS-2/3 actuation in order to bound LMi sequences.
- The final step of the WEC methodology is to evaluate such bounding sequences by using DSA methodologies, Table 1, and the corresponding WEC T/H codes (NOTRUMP/LOCTA Meyer, 1985 and (Shimeck and Hartz, 2000), WCOBRA/TRAC (Hochreiter et al., 1998) to show if adequate core cooling is achieved and therefore T/H uncertainties are bounded (Westinghouse Electric Company, 1997).

With respect to the DSA methodologies, it must be pointed out that, WEC follows SSG-2 option 3 methodology for bounding sequences BS-D and BS-E and SSG-2 option 1 methodology for the other bounding sequences, see (IAEA, 2009) for more details. The results obtained by WEC (last column in Table 4) show that are several short-term and long-term bounding sequences with

core uncoverly in MAAP simulations which did not present core uncoverly with NOTRUMP.

The UPM group has reproduced the whole process for all the ETs proposed by WEC for potential expansion (Westinghouse Electric Company, 2003a): Medium break LOCA (MBLOCA), CMT line break (CMT), DVILB, LBLOCA and Spurious actuation of ADS (SADS). The first three ETs correspond to medium LOCA trees (2 in.<D<9 in.) and the last two ETs correspond to large LOCA. With this aim, the so called SSG-2 option 2 (IAEA, 2009) has been used to verify the low-margin bounding sequences, which includes the use of a best-estimate computer code (TRACE) US Nuclear Regulatory Commission, 2007. However, conservative initial conditions and assumptions are still used.

As an example, Figs. 4 and 5 show the ET expansion process for the DVILB initiating event reproduced by UPM. Furthermore, only sequences with successful injection of IRWST are considered since IRWST failure sequences are core damage sequences. Once the ETs have been expanded, different kind of sequences can be identified within them, Fig. 5:

- Sequences coming from the conventional ET (DTn).
- Sequences which conform the complete EET (DXm).
- Low-margin sequences with potential contribution to CDF or LRF, Table 2 (DFi).

Table 4

Low-margin bounding sequences identified by WEC (BS-k) (Westinghouse Electric Company, 2003a).

Bounding sequence	Initiating event	CI	IRWST & RECIRC	CMT	ACC	ADS-4	PRHR	Bounds LMi Sequences	PCT (K). NOTRUMP or WCOBRA/TRAC
Short-term Cooling									
BS-A	Hot leg break (3.0 in.)	No	Yes	0	1	4	Yes	3,10,12,13	670 (N)
BS-B	Double-ended CMT balance line (6.8 in.)	Yes	Yes	0	2	4	Yes	4,5	No core uncoverly (N)
BS-C	Double-ended DVI line (4 in.)	No	Yes	1	0	3	No	1,7,9,11	1127 (N)
BS-D	Double-ended cold-leg LBLOCA (2x22in)	No	Yes	2	2	4	Yes	8	1286 (WC/T)
BS-E	Spurious ADS-4 (4x11 in.)	No	Yes	1	1	4	Yes	2,6	845 (WC/T)
Long-term Cooling									
BS-F	Double-ended DVI line (4 in.)	Yes	1/1&1/1	1	0	3	No	1-5,7,9,10	No core uncoverly (N)
BS-G	Double-ended DVI line (4 in.)	No	1/1&1/1	1	0	4	No	6,8,11-13	No core uncoverly (N)

Table 5

Important sequences associated to each EET for potential CDF.

Initiating event	DFi	LMI	LMI CDF (contribution%)	BS-k
DVILB	DF1, DF3, DF11, DF12, DF13, DF18, DF22, DF23	LM1, LM3, LM11, LM12	1.20E-6 (445.3%)	BS-C, BS-F, BS-G
SPADS	DF2, DF6, DF15 DF16 DF17 DF20	LM2, LM6	5.5E-7 (227.9%)	BS-E
MBLOCA	DF4, DF7, DF10, DF24	LM4, LM7, LM10, LM13	3.22E-7 (133.6%)	BS-A
CMTLB	DF5, DF9, DF14, DF25	LM5, LM9	1.40E-7 (58.4%)	BS-B
LBLOCA	DF8	LM8	8.52E-9 (3.5%)	BS-D

CDF, Table 3 and Table 5, indicates that many of these sequences could potentially increase the **AP1000** CDF, therefore it is necessary to verify these sequences adequately.

4. AP1000 LOCA sequences overview

This section is intended to describe the behavior of the **AP1000** reactor in case of LOCA sequences since all the low-margin sequences, that will be analysed thereafter, are different kinds of LOCA sequences (namely being BS-A, BS-B and BS-C MBLOCAs, and BS-D and BS-E LBLOCAs). In the following, a brief explanation about the phenomenology in case of MBLOCA and LBLOCA will be given.

As in a typical PWR, during a MBLOCA the RCS depressurizes rapidly. When the pressure drops to the reactor-trip setpoint (124 bar) the control rods are inserted, thus stopping the chain reaction. Subsequently, the RCS pressure decrease to the safety-injection signal setpoint (117 bar) aligning the passive core cooling system, namely CMTs, ACCs, IRWST and operation of PRHR and automatically tripping the Reactor Coolant Pumps (RCPs). The main BE setpoints for LOCA sequences are collected in Table 6. Four different phases can be identified in the **AP1000** reactor during MBLOCA sequences, see references (Lafi and Reyes, 1999; Friend et al., 1997; Wright, 2007; Montero-Mayorga et al., 2015) for more details:

- *Blowdown.* The Blowdown phase corresponds to the initial pressure decreasing where the reactor trip and **S** signal are triggered.
- *Natural circulation.* Natural circulation phase is the period in which, after the trip of the RCPs, the RCS is cooled by natural circulation paths. When the valves of the CMTs and PRHR open, three additional natural circulation paths are established providing core cooling leading the RCS pressure to values below of SG pressure (Montero-Mayorga et al., 2015). This period ends

with ADS-1 actuation. Unlike typical PWRs the steam generators are not as important during MBLOCAs in **AP1000** since the PRHR is activated very early in the accident and the IRWST serves as primary heat sink (Montero-Mayorga et al., 2015). The CMTs remain in recirculation mode and steam starts to replace water at the top of the tanks until the level in at least one CMT reaches about the 67.5% level and the ADS actuation signal is activated.

- *ADS blowdown.* Once 1 out of 2 CMTs level is about 67.5% the ADS-1 valves open automatically, at this time the ADS blowdown phase starts. After a short delay, ADS-2/3 actuate. When at least one CMT reaches about 20% level, the ADS-4 valves open. Thanks to the pressure reduction through the ADS valves as well as through the break, the setpoint for ACC actuation is reached (49 bar). This fact makes possible that the borated water contained in the ACCs drains into the RCS. ACCs injection stops partial or totally the flow from the CMTs due to the larger ACCs flow through the DVIs.
- *IRWST injection.* The short-term cooling ends with the IRWST injection phase. The actuation of the ADS-4 helps to reduce the RCS pressure near to containment pressure allowing the injection of borated water from the IRWST by gravity. After that, long-term cooling for MBLOCA is established.

In case of LBLOCA or spurious ADS-4 actuation the RCS depressurizes very fast to atmospheric conditions and the ADS-1/2/3 are not necessary to allow ACCs injection. This kind of scenario presents the following phases (Queral et al., 2015):

- *Blowdown.* Two sub-phases can be differentiated during this period, early and late blowdown, (Lime et al., 1994). During early blowdown (0.0 to 15 s) a fast depressurization of the RCS is produced. The core becomes almost completely voided in about 2 s.

The rapid loss of coolant causes fuel cladding temperatures to increase rapidly, producing a first maximum. Subsequently, during late blowdown (15–35 s) the ACC setpoint is reached and start to discharge. During a few seconds (typically 10 s) the flow injected by the ACCs is bypassed towards the broken loop due to the lower pressure in the break location.

- *Refill.* After further depressurization, the steam flow has dropped to a sufficiently low value that it cannot longer restrict the ingress of ACC water through the downcomer. The water injected by the ACCs reaches and refills the lower plenum during the next 15 s. At this time the fuel cladding temperatures continues rising.
- *Reflood.* Once the lower plenum has been refilled, core reflood and quenching begins. The rewet produces a larger amount of steam which is able to cool the upper part of the core. Thus, the fuel temperatures reach a maximum and then start to decrease. The end of reflood occurs 200 s later.

Table 6

Main setpoints for LOCA sequences (Westinghouse Electric Company, 2008) (BE values).

System	Setpoint
Reactor SCRAM	124 bar
S signal	117 bar
CMT injection	S signal + 2 second delay
SG main FW valves start to close	S signal + 5 second delay
RCP trip	S signal + 6 second delay
PRHR alignment	S signal
ACC injection	49 bar
ADS-1	CMT low level (67.5%)
ADS-2	48 second after ADS-1
ADS-3	120 second after ADS-2
ADS-4	128 second after ADS-3 & CMT low-low (20%)
IRWST squib valves open	ADS-4 actuation

The sequences which are analysed in this paper present unavailability of several of the systems commented above, therefore the low-margin bounding sequences will be different in some points of the sequence evolution compared with a standard LOCA.

5. AP1000 TRACE model nodalization and hypotheses

The **AP1000** TRACE model used through the analysis consists of all the main components such as Vessel, Steam Generators, Pressurizer, RCPs and connecting pipes as well as the passive safety systems, CMTs, ACCs, ADS and PRHR. No active systems are implemented in this model. The total number of thermal hydraulic components included in the TRACE model is 368, being 86 PIPES, 191 HTSTRs, 3 POWERS, 44 VALVES, 4 PUMPS, 24 BREAKs, 10 TEEs, 3 FILLS and 3 VESSELS, see Fig. 6.

The reactor vessel is modeled in three-dimensional cylindrical coordinates, with four radial rings and 17 axial levels. Two TRACE vessels are used to model the vessel, the first vessel component models the lower plenum, core and upper plenum. The second vessel component is used to model the downcomer with two radial rings, eight azimuthal sectors and 13 axial levels. The ADS is modeled such as the actual design, with the first 3 stages connected from the top of the pressurizer to the IRWST and the fourth connected to both hot legs. Safety relief valves and pilot operated relief valves are implemented in steam lines as well. The IRWST is modeled with a Cartesian vessel of 4 axial levels. The model also implements several controls such as PZR level and pressure, SG level and safeguards signals (e. g. reactor trip, safety injection and RCP trip).

In addition, 119 TRIPS, 377 CONTROL BLOCKS and 447 SIGNAL VARIABLES complete the model. In Table 7, the steady-state values achieved with TRACE are compared with the steady-state values of **AP1000** plant design (Westinghouse Electric Company, 2008). In addition main conservative hypotheses considered in the model are listed in Table 8.

This model has been previously applied in different LOCA analysis including the assessment of deterministic safety analysis for SBLOCA, MBLOCA and also LBLOCA sequences, see (Montero-Mayorga et al., 2015, 2014; Queral et al., 2015; Queral and Montero-Mayorga, 2016).

6. Analyses of AP1000 low-margin bounding sequences based on best-estimate calculations

As described in the previous section, once the low-margin bounding sequences (BS-k) have been identified, DSA methodolo-

Table 7
Steady-state values for **AP1000** TRACE-model.

Variable	TRACE BE	Plant design
Thermal power (MWt)	3415.0	3415.0
PZR pressure (bar)	155.8	155.1
Vessel inlet temperature (K)	552.4	553.7
Vessel outlet temperature (K)	595.9	594.1
Vessel Flow mass flow rate (kg/s)	14373.6	15100.0
SG pressure (bar)	55.4	57.6
Feed Water temperature (K)	499.72	499.85
Feed Water mass flow rate (kg/s)	1912.0	1885.0

Table 8
Main conservative hypotheses implemented in the **AP1000** TRACE model.

Nominal core power	102%
Decay Heat	ANS-1971 +20%
ACC pressure set-point	49 bar
IRWST, ACC and CMT temperature	321.8 K
Main feed water valves closing time	Between 2 and 7 second after S signal
SG isolation	6 second after reactor trip
SG Safety valves setpoint	85.14 bar
Safety injection	Friction factors increased in discharge lines

gies are used to evaluate these sequences in order to demonstrate that T/H uncertainties are bounded. As shown in Table 4, five short-term bounding sequences and two long-term bounding sequences were determined (Westinghouse Electric Company, 2003a). The results obtained by WEC (last column of Table 4) shows that only four low margin bounding sequences present core uncover but they do not exceed Peak Cladding Temperature (PCT) acceptance criterion in any case ($PCT < 1477$ K).

The UPM group has verified all the short-term BS-k sequences with the best-estimate TRACE code applying a SSG-2 option 2 methodology in order to verify the results obtained by WEC which applied SSG-2 option 1 and option 3 methodology with NOTRUMP/LOCTA and WCOBRA/TRAC codes respectively. As mentioned previously, the considered **AP1000** TRACE model implements some conservatisms from DCD chapter 15, Table 8. The bounding sequences that are simulated and analysed are:

- BS-A. Hot leg break (3 in.)
- BS-B. Double-ended guillotine break (DEGB) in CMT balance line (6.8 in.)

Fig. 6. **AP1000** TRACE model in SNAP nodalization.

- BS-C. DEGB in DVI line (2×4 in.)
- BS-D. DEGB in cold leg (2×22 in.)
- BS-E. Spurious ADS-4 actuation (4×11 in.)

All of these BS-k sequences have core uncover according to MAAP simulations, and all of them (except of BS-E) require ADS-4 actuation, IRWST injection and recirculation. On the other hand, all the LMi sequences include ADS-2/3 actuation but none of the BS-k sequences include this ADS actuation.

As it is stated in the PRA analysis, in the medium LOCA sequences where both CMTs fail to inject (BS-A, BS-B), automatic actuation of PRHR is required to provide adequate time for the operators to actuate the ADS-4 manually (Westinghouse Electric Company, 2003a). All the BS-k sequences with manual ADS-4 actuation (BS-A, BS-B) perform this human action at 20 min after the S signal which corresponds to its available time (Westinghouse Electric Company, 2003b).

It must be remarked that NOTRUMP simulations (BS-A, BS-B and BS-C) include a conservative RCP trip delay (S signal + 16 s, see (Westinghouse Electric Company, 2003a) instead of the BE value included in TRACE model (S signal + 6 s, see Westinghouse Electric Company, 2008 chapter 15).

6.1. Hot leg break. Low-margin bounding sequence A (BS-A)

BS-A sequence, presents the following safety systems availability for the accident mitigation: no CMTs, no ADS-1/2/3, credit for 4 out of 4 ADS-4 valves, 1 out of 2 ACCs, 1 out of 2 IRWST injection lines and PRHR actuation, Fig. 7.

The break size of this sequence (3 in.) was selected because the ACC injection occurs at the time the operators actuate the ADS-4 manually (Westinghouse Electric Company, 2003a). Since in this sequence the CMTs fail, the RCS pressure remains above ACC pressure injection until the operator actuate the ADS. That results in a period of 20 min in which no water is refilling the RCS. Thus, core uncover can be reached until ACC injection.

The TRACE results are plotted comparing with those obtained with NOTRUMP by WEC (Westinghouse Electric Company, 2003a) and the chronology of the sequence is presented in Table 9.

The results obtained with TRACE show a good agreement with the NOTRUMP ones. As it is depicted in Fig. 8, the pressure decreases until 75 bar where stabilizes for a period of about 500 s. Then, the pressure decreases linearly down to the manual actuation of ADS-4 is performed (1200 s after S signal) (Westinghouse Electric Company, 2003a). This ADS-4 actuation allows the ACC discharge, Fig. 9. Subsequently and due to reaching nearly atmospheric conditions, the IRWST starts to discharge water into the RCS, Fig. 9. It is appreciable that the TRACE IRWST mass flow is higher than the NOTRUMP one, probably due to a more conservative model in NOTRUMP (e.g. larger friction values). Previous SBLOCA (2 in.) analysis showed a similar IRWST mass flow discrepancy between both codes, see (Montero-Mayorga et al., 2015). However, in other LOCA cases with higher break sizes a similar IRWST mass flow was observed for TRACE and NOTRUMP simulations, see (Montero-Mayorga et al., 2015).

In both simulations, the minimum predicted RCS inventory is quite similar, Fig. 10. However, after 1500 s the RCS inventory presents some differences due to the greater makeup from the IRWST in TRACE. It must be noted, that in the NOTRUMP case a small core uncover can be appreciated near to the ADS actuation (PCT = 670 K), see Westinghouse Electric Company, 2003a and Fig. 11. However, such behavior is not predicted with TRACE, probably due to the greater RCS inventory until the ADS is manually actuated, Figs. 11 and 12.

6.2. DEGB in CMT balance line. Low-margin bounding sequence B (BS-B)

BS-B sequence presents the following safety systems availability for the accident mitigation: no CMTs, no ADS-1/2/3, credit for 4 out of 4 ADS-4 valves, 2 out of 2 ACCs, 1 out of 2 IRWST injection lines and PRHR actuation, Fig. 13.

The TRACE results are plotted comparing with those obtained with NOTRUMP by WEC (Westinghouse Electric Company, 2003a) and the chronology of the sequence is presented in Table 10. The results obtained with TRACE shows a good agreement with the NOTRUMP ones.

Fig. 7. Hot Leg LOCA (BS-A). Availability of safety systems.

Table 9
Hot Leg LOCA (BS-A). Sequence chronology.

Event	TRACE (s)	NOTRUMP (s)
Break occurs	0.0	0.0
Reactor trip	27.0	39.0
S signal	35.0	47.0
RCP trip	41.0	63.0
ACC injection starts	1200.0	1200.0
Manual ADS-4 actuation	1235.0	1247.0
IRWST injection	1283.0	1500.0

The results of both codes show that the CMT line break (6.8 in.) results in a rapid RCS depressurization and ACCs injection, Figs. 14 and 15. Once the ACCs are empty there is no more injection capability until the IRWST injects, and then it is necessary to actuate manually the ADS-4 in order to depressurize the RCS until

atmospheric conditions before the ACCs are empty (about 1200 s after S signal) (Westinghouse Electric Company, 2003a). This human action allows maintaining the core covered and therefore high PCT values are not reached, Figs. 16–18.

6.3. DEGB in DVI line. Low-margin bounding sequence C (BS-C)

BS-C sequence presents the following safety systems availability: 1 out of 2 CMT (intact loop), 0 out of 2 ACC, ADS-1/2/3 failed, credit for automatic actuation of 3 out of 4 ADS-4 valves and the IRWST corresponding to the intact line, see Fig. 19. The size of the DVI line is 6.8 in. 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 discharged through the break. It must be remarked that this bounding sequence is quite important since it bounds the low-margin sequence with largest

Fig. 8. RCS pressure (Hot Leg LOCA, BS-A).

Fig. 9. ACC and IRWST injection (Hot Leg LOCA, BS-A).

Fig. 10. RCS Inventory (Hot Leg LOCA, BS-A).

Fig. 11. Core liquid volume (Hot Leg LOCA, BS-A).

Fig. 12. PCT (Hot Leg LOCA, BS-A).

contribution to potential CDF and LRF (LM1) but also LM7, LM9 and LM11 sequences, see Table 4.

TRACE results are plotted comparing with those obtained by WEC with NOTRUMP code (Westinghouse Electric Company, 2003a) and the chronology of the sequence is presented in Table 11. As it is depicted in Fig. 20 and Fig. 22, the pressure and RCS inventory transient presents a similar trend in both cases and the automatic actuation of ADS-4 is achieved close to 1550s for WEC and UPM simulations.

In this sequence the available CMT is the only way to cool the core until the ADS-4 actuation allows the injection of the IRWST. Although the CMT flow predicted by TRACE is slightly greater, Fig. 21, the trend is quite similar for both codes. The time in which the ADS-4 actuates (CMT level = 20%) is appreciable in both cases since the CMT mass flow rate is increased, Fig. 21, and the RCS pressure drops simultaneously, Fig. 20.

Later, when the IRWST injection is achieved, the RCS is again pressurized above the IRWST injection pressure, which produces

Fig. 13. DEGB in CMT balance line (BS-B). Availability of safety systems.

Table 10
DEGB in CMT balance line (BS-B). Sequence chronology.

Event	TRACE (s)	NOTRUMP (s)
Break occurs	0.0	0.0
Reactor trip	10.0	10.7
S signal	12.0	16.7
RCP trip	18.0	32.7
ACCs injection starts	233.0	290.0
Manual ADS-4 actuation	1212.0	1217.0
IRWST injection	1388.0	1450.0

Fig. 14. RCS pressure (DEGB in CMT balance line, BS-B).

a short interruption in the IRWST mass flow rate, Fig. 21. The minimum core level is reached at about 1900s producing a fast PCT rise. When the water from the IRWST flows into the system, the core level is recovered and the temperatures decrease. It is appreciable that the PCT value obtained with NOTRUMP (1127 K), Table 4, is higher than the obtained with TRACE code (871 K), Fig. 23 and Fig. 24. This is an expected result since NOTRUMP analysis includes more conservative models and assumptions than TRACE.

Fig. 15. ACCs and IRWST injection (DEGB in CMT balance line, BS-B).

Fig. 16. RCS Inventory (DEGB in CMT balance line, BS-B).

Fig. 17. Core liquid volume fraction (DEGB in CMT balance line, BS-B).

Fig. 18. PCT (DEGB in CMT balance line, BS-B).

6.3.1. Sensitivity to CMT availability

In this section a modified BS-C sequence which considers 2 out of 2 CMTs instead of 1 out of 2 CMTs is analysed. The previous analysis of BS-C assumes the hypothesis that the CMT connected to the broken DVI is not available. However, it must be reminded that the discharge of the CMT demands the actuation of ADS-1 at 67% CMT level and subsequently the ADS-4 at 20% CMT level. Therefore, if the CMT located in the broken loop is available, it could discharge its entire inventory in a short time, demanding the automatic actuation of ADS-4 and producing a large break in the hot legs (ADS-4 valves) along with the break of one of the DVI lines. Moreover such sequence is more likely than a sequence in which one of the CMTs is not available.

Although this modified sequence is not considered as low-margin bounding sequence, the UPM group decided to perform this sensitivity analysis in order to check that no worse consequences would be expected in this case. As commented beforehand, the

Table 11

DVILB (BS-C). Sequence chronology.

Event	TRACE (s)	NOTRUMP (s)
Break occurs	0.0	0.0
Reactor trip	24.3	13.4
S signal	27.2	20.0
RCP trip	33.2	36.0
CMT injection starts	39.2	N/A
Auto ADS-4	1355.0	1380.0
IRWST injection	1870.3	1960.0
Maximum PCT	1995.1	≈2200.0

CMT in the broken line discharges very quickly, Fig. 25, demanding ADS-4 actuation before in the case where the CMT is available, Fig. 26. Thus, a faster depressurization transient is appreciated, Fig. 27.

Fig. 19. DVILB (BS-C). Availability of safety systems.

Fig. 20. Pressure transient (DVILB, BS-C).

Fig. 23. Core liquid volume fraction (DVILB, BS-C).

Fig. 21. CMT and IRWST injection mass flow rate (DVILB, BS-C).

Fig. 24. PCT (DVILB, BS-C).

Fig. 22. RCS Inventory (DVILB, BS-C).

Fig. 25. CMTs mass flow (BS-C). Sensitivity to CMT availability.

However, contrary to the behavior that could be expected due to the faster depressurization, the IRWST injection does not inject earlier. Such fact is due to the injection provided by the CMT. This system is driven by the steam produced in the cold legs which pushes the water contained in CMTs and until this system is not empty, the IRWST cannot inject properly in both cases.

Nevertheless, an appreciable difference between both cases is observed. When the IRWST is able to inject in BS-C, the RCS pressurizes above IRWST injection pressure during a short period producing a short cut off in IRWST injection and therefore a rise in PCT, Figs. 28 and 29. This behavior is not predicted in the modified sequence because when the IRWST starts to inject, the RCS is not

Fig. 26. ADS-4 mass flow (BS-C). Sensitivity to CMT availability.

Fig. 29. PCT (BS-C). Sensitivity to CMT availability.

Fig. 27. RCS pressure (BS-C). Sensitivity to CMT availability.

Fig. 30. Core Level (BS-C). Sensitivity to CMT availability.

Fig. 28. IRWST injection (BS-C). Sensitivity to CMT availability.

pressurized as in BS-C and therefore the IRWST injection remain providing water in a suitable way.

Concerning to the core level, due to the earlier depressurization produced in the modified BS-C sequence because of ADS demand, the core level reaches a minimum close to 20% and stabilizes afterwards at 40%, Fig. 30. In BS-C, the core level decreases quickly

Table 12
Sensitivity to CMT availability. Main events.

Event	BS-C 1 out of 2 CMT	Modified BS-C 2 out of 2 CMT
ADS actuation (s)	1355.0	300.0
CMT empties (s)	1620.0	1550.0
IRWST injection starts (s)	1870.0	1860.0
Minimum core level during blowdown (%)	55.0	25.0
Maximum PCT (K)	871	726

Table 13
Large Break LOCA (BS-D). Sequence chronology (TRACE code).

Event	Time (s)
Break occurs	0.0
S signal	4.0
CMT injection starts	5.0
RCP trip	10.0
CMT injection paused	14.0
ACC injection starts	14.0
PCT occurs	50.0
CMT injection resumed	250.0
IRWST injection	1210.0

when the ADS-4 is automatically actuated at 1200 s, then the core level is similar in both cases and stabilizes at 50% providing long term cooling. Table 12 collects main events of both sequences.

These sensitivity analysis results, Table 12, allow to confirm that BS-C is actually more limiting than the proposed modified BS-C sequence.

6.4. DEGB in cold leg. Low-margin bounding sequence D (BS-D)

BS-D sequence presents the following safety systems availability: 2 out of 2 CMTs, 2 out of 2 ACCs and 1 out of 2 IRWST injection lines. This sequence, DEGB in cold leg, is analysed in the **AP1000** DCD chapter 15 by means of the best-estimate plus uncertainty ASTRUM methodology with WCOBRA/TRAC code, which corresponds to a SSG-2 option 3 methodology, see (Westinghouse Electric Company, 2008; US Nuclear Regulatory Commission, 2007) for more details. The differences between DCD LBLOCA best-estimate case and BS-D are, see (Westinghouse Electric Company, 2003b) section 15.0.12.3 and (Westinghouse Electric Company, 2003a),

- Offsite power is available until the RCPs are tripped in BS-D, but DCD case includes loss of offsite power at the time of the break and then RCPs are also tripped at the time of the break.
- DCD LBLOCA single failure hypothesis: One CMT valve fails to open. However, BS-D configuration includes 2 out of 2 CMTs available.

- The containment isolation is failed in BS-D, so that the containment is at atmospheric pressure.

The UPM group has simulated this sequence based on the same methodology and conservative hypotheses used for the other bounding sequences (SSG-2 option 2).

TRACE results are plotted comparing with those obtained by WEC with WCOBRA/TRAC code and the chronology of the TRACE sequence is presented in Table 13 (WCOBRA/TRAC chronology is not available in open literature). As it can be seen in Figs. 31–34, the predicted behavior is quite similar for both codes. One of the differences that can be appreciated corresponds to core level stabilization when such level is recovered, Fig. 32, which remains lower in the case of UPM. This fact produces the need of 100 s more to achieve successful core cooling in the hottest rod, Fig. 33. In both cases, the PCTs are far away from the acceptance criterion. WEC predicted for BS-D a best-estimate PCT value of 1159 K and then estimated the 95th percentile by adding the difference between:

- DCD LBLOCA analysis best-estimate reference case (1308 K)
- DCD LBLOCA result with uncertainty (1435 K).

Such difference ($1435 - 1308 = 127$ K) is added to BS-D best-estimate value to estimate the 95th percentile, 1286 K (Westinghouse Electric Company, 2003a). It must be noted that the maximum value for 95th percentile PCT in WEC case (1286 K) is slightly greater than the value obtained by UPM (1234 K).

Fig. 31. RCS pressure (DEGB in cold leg, BS-D).

Fig. 33. PCT (DEGB in cold leg, BS-D).

Fig. 32. Core Level (DEGB in cold leg, BS-D).

Fig. 34. Passive safety systems injection (DEGB in cold leg, BS-D). Extended view.

6.5. Spurious ADS-4 actuation. Low-margin bounding sequence E (BS-E)

BS-E sequence presents the following safety systems availability: 1 out of 2 CMTs, no ADS-1/2/3, 1 out of 2 ACCs, IRWST injection and PRHR actuation, Fig. 35. This case was analysed by WEC with the best-estimate WCOBRA/TRAC computer code (Zhang et al., 1998) and considering similar hypotheses and methodology as the ones for BS-D.

TRACE results are plotted comparing with those obtained by WEC with WCOBRA/TRAC code and the chronology of the TRACE sequence is presented in Table 14. Regarding the comparison of results between both codes, a very similar trend is obtained for the main variables. The pressure reaches the ACC pressure injection almost at the same time in both simulations, Fig. 36, although the discharge ends slightly later in case of WCOBRA/TRAC, Fig. 37. As it can be appreciated in Fig. 38, after ACC injection the core level is recovered and is maintained with the actuation of CMT and IRWST, Fig. 40. Finally, the PCT obtained in both analysis is quite similar, Fig. 39. It must be noted that, in the same way of BS-D sequence, WEC predicted for BS-E a best-estimate PCT value of 718 K and then the estimated 95th percentile by adding the previous difference obtained for BS-D. Such difference (127 K) is added to the best-estimate BS-E value obtaining the mentioned 845 K (Westinghouse Electric Company, 2003a). This 95% percentile PCT value is greater than PCT value obtained with TRACE (701 K).

6.6. Main results obtained in low-margin bounding sequences analysis with TRACE

The PCT obtained in short-term low-margin bounding sequences with TRACE using SSG-2 option 2 along with the ones for WEC using SSG-2 options 1 and 3 are collected in Table 15. The comparison allows verifying the results predicted by WEC by using different T/H codes, NOTRUMP (N) and WCOBRA/TRAC (WC/T). In general the PCT predicted with TRACE when there is

Table 14

Spurious ADS-4 actuation (BS-E).
Sequence chronology (TRACE code).

Event	Time (s)
ADS-4 valves open	0.0
Reactor trip	6.5
S signal	8.0
RCP trip	14.0
CMT injection starts	19.0
ACC injection starts	41.0
Maximum PCT	91.0
IRWST injection starts	470.0

Fig. 36. RCS pressure (Spurious ADS-4 actuation, BS-E).

core uncover is very similar to WEC results with exception of BS-C. Moreover no core uncover is obtained with TRACE for BS-A and BS-B. It must be noted, that all these BS-k sequences where core uncover sequences when they were simulated with MAAP. This result also indicates that the use of MAAP seems to be adequate for **AP1000** PRA Level 1.

Fig. 35. Spurious ADS-4 actuation (BS-E). Availability of safety systems.

Fig. 37. ACC injection (Spurious ADS-4 actuation, BS-E).

Fig. 38. Core level (Spurious ADS-4 actuation, BS-E).

Fig. 39. PCT (Spurious ADS-4 actuation, BS-E).

7. Conclusions

This paper summarizes and verifies, the low-margin sequences evaluation process developed by WEC in order to bound the T/H uncertainties that can affect to the PRA success criteria. Moreover, this study has verified with the best-estimate TRACE computer code, by means of SSG-2 option 2, the low-margin bounding

Fig. 40. CMT and IRWST mass flow (Spurious ADS-4 actuation, BS-E).

Table 15

Main results obtained for PCT in BS-k sequences. Comparison with WEC results.

Initiating event	TRACE (K)	WEC (K)
Hot leg break (BS-A)	No core uncover	670 (N)
DEGB in CMT balance line (BS-B)	No core uncover	No core uncover (N)
DEGB in DVI line (BS-C)	871	1127 (N)
DEGB in cold leg (BS-D)	1234	1286 (WC/T)
Spurious ADS-4 actuation (BS-E)	701	845 (WC/T)

sequences identified and evaluated by WEC using NOTRUMP (BS-A, BS-B and BS-C) and WCOBRA/ TRAC (BS-D and BS-E).

The results show a similar trend between TRACE-NOTRUMP and TRACE-WCOBRA/TRAC. However, some differences are observed in the discharge of IRWST for small break sizes (3 in. hot leg break) in which NOTRUMP presents mass flow rate values which are almost a half of the predicted by TRACE. Such behavior was also observed in Friend et al. (1997) where this issue was analyzed in deep and the main reason for this behavior is the sensitivity of IRWST capacity to inject close to atmospheric conditions. Regarding the sequences in which core uncover is found, the analysis show that a lower PCT value is always obtained in TRACE simulations with SSG-2 option 2. Nonetheless, all of them remain well below from the PCT acceptance criterion (1477 K).

As a global conclusion, this analysis has allowed to verify the AP1000 T/H uncertainty evaluation process performed by WEC for the most risk-important low-margin sequences with a best-estimate code such as TRACE applying SSG-2 option 2 approach.

This work has allowed enlarging the set of DSA and PRA verifications related with different AP1000 sequences by means of TRACE code in the framework of the ISAMAR project. New PRA and DSA verification analyses will be performed in future works.

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.

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