CONTAINMENT RESPONSE TO A SEVERE ACCIDENT (TMLB SEQUENCE) WITH AND WITHOUT MITIGATION STRATEGIES

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ABSTRACT

A loss of SG feed-water (TMLB sequence) for a prototypic PWR 900 MWe with a multi-compartment configuration (with 11 and 16 cells nodalization) has been calculated by means of the ASTEC code. A variety of hypothesis (e.g. activation of sprays and hydrogen recombiners) and possible consequences of these assumptions (cavity flooding, hydrogen combustion, etc.) have been made in order to evaluate the global reactor containment building response (pressure, aerosol/FP concentration, etc.).

The need to dispose of severe accident management guidelines (SAMGs) is increasing. These guidelines are meant for nuclear plants' operators in order to allow them to apply mitigation strategies all along a severe accident, which, only in its initial phase, may last several days. The purpose of this paper is to outline the influence on the containment load of most common accident occurrences and operators actions, which is essential in establishing SAMGs.

ASTEC (Accident Source Term Evaluation Code) is a computer code for the evaluation of the consequences of a postulated nuclear plant severe accident sequence. ASTEC is a European computer tool currently under development by the "Institut de Radioprotection et de Sûreté Nucleaire (IRSN)", France, and "Gesellschaft für Anlagen-und Reaktorsicherheit (GRS)", Germany. The aim of the development is to create a fast running integral code package, reliable in all simulations of a severe accident, to be used for level-2 and level-3 PSA analysis.

It must be said that several recent developments have significantly improved the "best-estimate" models of ASTEC. However, the somehow obsolete ASTECv0.3 version, which has been here used, has given results very useful for the estimation of the global risk of a nuclear plant.

Moreover, under the current 6th FWP, the SARNET project (Sustainable Integration of EU Research on Severe Accident Phenomenology and Management) has also the target to involve Ph.D. students and researches in the "education & training" elements of ASTEC development. And in this framework ASTEC has shown a very good capability for being used as an investigative tool as well as an educational & training tool. In this paper, ASTECv0.3 is compared to MELCOR and CONTAIN codes in order to show the high degree of confidence which can be already placed in the ASTEC tool.

1 INTRODUCTION

The ASTEC code system[/1/] has been designed for the evaluation of the response of nuclear plants during hypothetical severe accidents. It is essentially the result of the merging of two calculation tools: ESCADRE[/2/] and RALOC/FIPLOC[/3/]. Containment thermal-hydraulic and aerosol behaviour models, from GRS, have been coupled in the CPA code (Containment Part of ASTEC), which is substituting the JERICHO and AEROSOLS-B2 codes.

ASTECv0.3 calculations have been run on a portable personal computer with 128 Mbytes RAM total memory and 300-400 MHz processor speed (Pentium II under the Windows 2000 operating system). Most of the TMLB sequences (and sub-sequences) which have been run in order to write the conclusions of this paper required much less than the problem time (i.e. < 12 hours). Only the calculations involving hydrogen burning needed a calculation time of the same order of magnitude of the problem time.

The TMLB sequence (T "transient event, M "failure of the secondary system steam relief valves and the power conversion system", L "failure of the auxiliary feed-water system", B "failure of the electric power to ESFs") here studied does not reflect any probabilistic criteria: it has not been chosen based on a probabilistic risk assessment, but rather with the objective of covering a sort of worst-case scenario.

2 PLANT NODALISATION

A prototypic 900 MWe PWR has been modelled using a nodalization with eleven and sixteen cells. The containment building has been modelled with (1) a "lower compartment" which includes the sump and the cavity sub-compartments, (2) a "medium compartment" where steam generators and the pressurizer are located, (3) a containment annulus and (4) an "upper compartment" or dome.

This scheme has been used to generate an 11 cell nodalization/4/, /5/ and /6/: the "medium compartment" has been divided into 8 sub-compartments, which accommodate: (1) the pressurizer, (2) the refuelling pool, (3) the vessel upper-head, (4) the first loop of the RCS, (5) the second loop of the RCS, (6) the third loop of the RCS, (7) the pressurizer relief tank and (8) the volume around the three loops of the RCS.

When the upper dome is divided into 6 further cells, a 16-cell nodalization is obtained. This more complex nodalization has been modelled with the CPA module, which deals with the containment thermal-hydraulics and aerosol behaviour. CPA is a multi-compartment computer code able to treat the containment building as several large compartments (almost empty spaces, such as the upper containment dome, or the annulus) connected by junctions describing the physical separations (doors, tunnels, small interfacing compartments, obstacles, etc.).

3 TMLB SEQUENCE MODELLING ASSUMPTIONS

The accident sequence here studied (TMLB sequence) is a sequence with a high pressure-melt ejection (HPME) from reactor vessel involving a partial corium entrainment from cavity. Thus, both MCCI (Molten Core-Concrete Interaction) and DCH (Direct Containment Heating) occur. The initiator event is loss of steam generator feed water with simultaneous unavailability of the emergency core cooling system (ECCS). Steam generators dry out early in the sequence, core heats up and PORVs open in order to avoid a dangerous pressurisation of the primary system.

Vessel pressure remains quite high (ranging between 160 and 165 bar) therefore accumulators cannot inject any coolant. During the core degradation phase, steam boil-off depends essentially on the decay heat level and the characteristics of the PORV. At this stage, hydrogen, structural materials and fission products, under gaseous and aerosol form, are released into the medium compartments through the PORV via the hot leg and the pressurizer surge line. From here they reach the upper dome.

DCH has an important impact on the sequence: vessel-driving pressure, which is even larger than operating RCS pressure, is causing a vigorous corium entrainment into the containment dome. However, DCH, induced by the entrained corium, and MCCI, caused by the corium mass left inside the cavity, may strongly vary depending on the cavity geometry and on the hydrodynamics of the blow-down through the compartment connecting the reactor cavity to the containment. Two different cavity geometries (i.e. cavity cross sections) have been here modelled in which either (1) carrier gas slows down within the cavity and total corium debris dispersal fraction out of cavity is small or (2) carrier gas maintains a high velocity and debris are able to escape with a larger dispersal fraction. These two cavity geometries have been characterised by a dispersal fraction as low as 37 % for the first case and as large as 89 % for the second case (see Table 1).

Further corium-coolant interaction is modelled to occur within the cavity after DCH (with the coolant from primary system which has fallen into the cavity and with water already contained in the cavity). Credit is not given to an abrupt steam explosion, but vigorous steam generation is predicted.

MCCI can be modelled by ASTEC either with a two-layer configuration (as in MELCOR) or with a mixed one, that is with a metallic phase dispersed in the oxide phase. This modelling option is conservative because it maximise metals oxidation and gives more uniform concrete erosion shapes. Reactor cavity basemat is assumed made of limestone concrete (56% $CaCO_3$, 25% SiO_2).

Additional events as intervention of passive safety systems and operators' actions (e.g. hydrogen recombination, spray activation, cavity flooding, containment venting, etc.) have been modelled/7/ and /8/ in order to evaluate the influence on the containment pressure load: fourteen calculations have been performed changing the parameters showed in Table 1. Timing for cavity flooding has been based on a criterion of erosion of cavity walls, but only in order to observe this phenomenology and estimate its influence.

Table 1: ASTECv0.3 calculation assumptions for the TMLB accident sequence.

TMLB sequence	Assumptions and occurrences
Initiator event	Transient, LOSP, Loss of steam generator feed water
Primary system pressure at vessel failure	High (>160 bar)
Emergency Core Cooling System	Off
Pressurizer Power-Operated Relief Valves (PORVs)	Regulation (160-165 bar)
Accumulators	Off
Spray activation	Yes/No (when pressure > 2.4 bar)
Fission product retention in primary circuit	No (SOPHAEROS is "off")
Iodine speciation between water pools and gas	No (IODE is "off")
Hydrogen combustion	Yes (at any time) / No Yes (Allowed after 30000 seconds from DCH) / No
Hydrogen recombination	Yes / No
Cavity flooding	Yes / No (early flooding when 0.05 m-cavity lateral erosion is reached) (late flooding when more than 0.5 m-cavity lateral erosion is reached)
Containment venting	Yes (above 5 bar but not allowed during DCH blow-down)
Corium entrainment (driving vessel pressure > 166 bar)	Dispersal fraction limited to ~ 37% for the 11 cell nodalization (cavity cross section=40 m^2) Dispersal fraction limited to ~ 89% for the 16 cell nodalization (cavity cross section=20 m^2)

4 CALCULATION RESULTS & ASTEC V0.3 / MELCOR 1.8.2 COMPARISON

Of the 14 calculations performed with the ASTEC code, two are here discussed essentially because they are directly comparable to the MELCOR and the CONTAIN calculations[/9/] (the validity of CONTAIN and MELCOR comparison is discussed in reference /9/). Main assumptions are here below:

Case #1 - Low containment pressure load

- 16 compartments;
- CORIUM module “off”;
- without spray;
- without H_2 combustion;
- without H_2 recombination;
- without cavity flooding;
- with large corium entrainment (dispersal fraction outside the cavity is ~ 89%).

Case #2 - High containment pressure load

- 11 compartments;
- CORIUM module “on”;
- without spray;
- with H_2 combustion allowed at any time;
- without H_2 recombination;
- with cavity flooding at the vessel failure;
- with moderate corium entrainment (dispersal fraction outside the cavity is ~ 37%).

The comparison of these two cases will show that the flooding of the cavity is the phenomenology, which causes the more important load to the containment: a large dispersion of corium outside the cavity has a lesser importance on the long-term containment load. Besides, as a consequence of the large dispersion, MCCI involves a smaller mass of corium with a lower generation of non-condensable gases. An increase of the number of compartments (from 11 to 16) shows negligible effects.

Modelled DCH assumes that, after the instantaneous thermal equilibrium between entrained corium and carrier gas, which occurs within the cavity, the carrier gas mixes with the containment atmosphere causing a sudden pressure increase (highest peaks in Figure 1). The CORIUM module of ASTEC assumes a further conservative thermal equilibrium between the corium, which has left the cavity (i.e. the dispersal fraction, DF) and the bulk of the containment atmosphere. In a less conservative approach this corium should have a weak interaction with containment gas because of impaction/deposition (i.e. retention) phenomena all along its path through the sub-compartmentalization between the cavity and the upper dome of the containment.

Among the potential sources of difference to take into account when comparing ASTEC and MELCOR results it should be stressed that MELCOR data refer to a TMLB' calculation for the Surry reactor/9/, that is a realistic variation of the TMLB sequence in which electrical power is postulated to be recovered in one to three hours (thus, fuel damage might be prevented since core uncovery and fuel degradation are generally predicted to start in about one to two hours after the blackout starts). However, the MELCOR 1.8.2 calculation predicts vessel failure and DCH occurrence, therefore the two sequences are essentially the same.

Reactor characteristics, as modelled in ASTEC, are very similar to those of Surry reactor (MELCOR & CONTAIN calculations): core volume and mass are about the same (Surry Unit 1 is a 815 MWe-reactor). They also have a similar containment: the free volume of Surry containment is 52773 m^3 whilst the one modelled in ASTEC has a total volume of 52263 m^3. However, cavity concrete characteristics are different: limestone concrete (modelled in the ASTEC calculation), through the MCCI, generates significant quantities of steam, H_2, CO_2 and CO, whilst basaltic concrete (as Surry's cavity basemat) generates mostly steam and H_2 (i.e. less non-condensable gas).

As regards the early phase of the accident, and before the vessel failure, the rate of loss of coolant is modelled to be lower in the MELCOR calculation, which results in a pressure load lower than the one predicted by ASTEC, as shown in Figure 1 (containment structures, which cause a strong condensation at this stage, are assumed to be similar). The stronger ASTEC-modelled boil-off to the containment will result in a faster core degradation (compare the timing of core uncovery, cladding oxidation, FPs release, etc. in Table 2 for ASTEC and MELCOR). However, after the bottom-head vessel failure the whole coolant inventory will contribute to the containment load and code predictions are again comparable.

Other differences between the ASTEC (case #1) and the MELCOR predictions (/"behaviour") are related to the:

1) core fraction participating to the HPME (MELCOR calculation assumes that only 15% of corium will contribute to the DCH phenomenology, whilst for ASTEC/case #2 (100-37)% of the corium is involved, but the two MCCIs are still comparable);

2) MCCI modelling (CORCON model assumes a layer flip in MELCOR);

3) a dry MCCI after 27500 seconds in MELCOR (because sump overflow into the cavity is not allowed);

4) an almost dry MCCI onset in the ASTEC/case #2 calculation because no much water is left inside the vessel at the time of the bottom head failure (and core temperature are higher for ASTEC at this time as shown in Table 1).

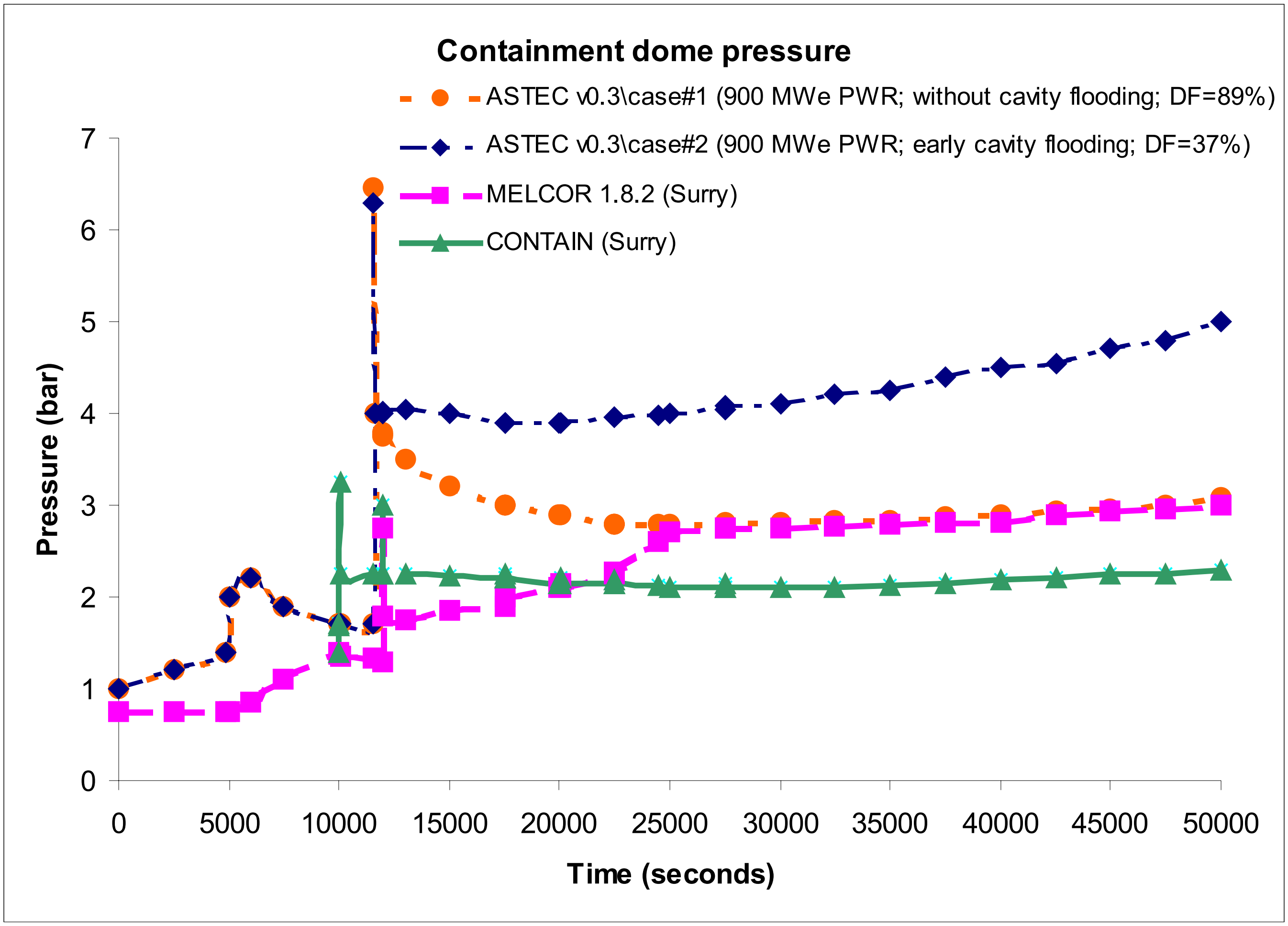

Figure 1: Containment dome pressure for a 900 MWe PWR (ASTECv0.3) and Surry reactor (MELCOR 1.8.2 and CONTAIN)

MELCOR predicts a weak pressure peak at the vessel failure (because of the assumption of a low corium dispersal from cavity –15%). Afterwards, containment pressure increases essentially because of water evaporation on corium surface (corium-coolant interaction). Pressure increase is also caused by the large amount of corium (85%), which remains in the cavity and takes part in the MCCI, but to a smaller extent: in fact, the MELCOR trend in Figure 1 shows that, once the corium upper surface is dry (at about 27500 s because sump overflow into the cavity cannot occur), the pressure increase rate is much lower. The predicted containment load, at this stage, is very close to the ASTEC prediction (case #1 without cavity flooding).
CONTAIN shows a mismatch of about 0.6 bar in the containment pressure prediction even at the late stage of the accident (but increasing with the same slope). CONTAIN (modelling the containment thermal-hydraulics) assumes the boil-off about 40 minutes before the vessel failure. Both MELCOR and ASTEC predict a vessel failure almost immediately after the time of the failure of the core support plate (Table 2). It must be said that more recent model developments assume a failure of the bottom head by creep which takes a longer time.

The pressure trend for ASTEC/case #2 shows a strong pressurisation of the containment because of the cavity flooding, which is assumed to occur, in this case, immediately after vessel failure.
It should be noted that in the MELCOR calculation if the corium-coolant interaction on the surface of corium inside the cavity could progress (because of cavity flooding) the extrapolation of the (MELCOR) trend would predict pressure values close to ASTEC/case #2 predictions. This reasoning may lead to state that this (ASTEC/case #2) relatively “heavy” DCH scenario contributes only to the early-phase of the accident, whilst the

Table 2: Timing of key-events and main sequence parameters as calculated by ASTEC (TMLB case #1–prototypic 900 MWe PWR) and MELCOR (reference calculation for the Surry 815 MWe PWR-TMLB' [/9/]).

TMLB sequence timing by ASTECv0.3		TMLB' by MELCOR 1.8.2
* 5.70500E+03	Start of core uncovery, TDEW (s)	7200 s
* 5.71000E+03	Start of cladding oxidation in the core (s)	10000 s
* 5.96940E+03	Start of FPs release from fuel pellets (s)	10235 s
* 7.34721E+03	First fuel cladding rupture (s)	10235 – 10668 s
* 7.57221E+03	Total core uncovery (s)	
* 1.04172E+04	Melting pool formation in the core (s)	
* 1.15672E+04	First lateral corium slump in vessel lower head (s)	11177 s (core support plate fails)
** 6.58813E+04	Resulting mass of corium in the lower head (kg)	
* 1.15672E+04	Lower head vessel failure (s)	11219 – 13842 s
** 1.19292E+04	Cumulated H2O mass leaked at breaks since TDEW (kg)	
** 3.28062E+02	Cumulated H2 mass leaked at breaks since TDEW (kg)	
** 3.27894E+02	H2 mass produced during the in-vessel phase (kg)	180 kg (at the vessel failure)
** 9.70878E+02	Aerosols mass in cont. at vessel failure (kg)	
* 1.15720E+04	End of corium slump from lower head vess. to cav. (s)	11219 s
** 1.19453E+05	Total mass of corium ejected from lower head (kg)	113000 kg
** 2.58458E+03	Temperature of corium ejected from lower head (°C)	2300 °C
* 1.15739E+04	End of corium droplets entrainment out of cavity(s)	11252 s
** 3.22617E+04	Corium mass entrained out of cavity to cont. (kg)	16950 kg
** 2.72842E+02	Temperature of corium/gas mixture entrained (°C)	
* 1.15780E+04	End of primary circuit gases blowdown (s)	11786 s
* 1.15780E+04	start of H2 combustion (s)	12863 s (in cavity)
* 1.17090E+04	overflow of the sump into the cavity (s)	Cavity dry-out at 27500 s
* 5.00000E+04	End of sequence calculation (s)	90000 s
** 5.75494E+02	H2 mass in containment after DCH (kg)	~225 kg
** 6.46475E+01	Aerosols mass in containment after DCH (kg)	
** 9.02799E+02	Final H2 mass in containment (kg)	~650 kg (if not burned)
** 5.89350E-01	Total H2 mass leaked outside containment (kg)	
** 0.00000E+00	Total H2 mass burnt in containment (kg)	
** 1.03553E+03	Final aerosols mass in containment (kg)	
** 3.64095E-02	Total aerosols mass leaked outside containment (kg)	
** 6.30873E+00	Pressure peak value (bars) reached in zone 2	
** 1.15769E+04	Time at which this pressure peak value was reached (s)	

cavity flooding phenomenology seems to contribute to the late phase. This is further validated by the fact that the worst-case DCH scenario (ASTEC case #1 which exhibits a dispersal fraction of 89%), without cavity flooding, shows even a decreasing pressure trend in the early phase. Only afterwards, because of MCCI, the pressure trend increases again in the late phase.

Hydrogen combustion does not contribute to a pressure increase: in both MELCOR and CONTAIN calculations at each deflagration the predicted pressure is slightly noticeable. Several intermittent hydrogen deflagrations occur inside the cavity at two different times: 12863-13766 s and 32970-44779 s), whilst they are not predicted to occur in the containment (outside the cavity), owing to steam and/or CO_2 inert conditions in the other compartments. Similarly, in the ASTEC calculations no hydrogen combustion is predicted in the containment dome.

In conclusion, from the comparison of ASTEC and MELCOR calculations it can be inferred that:

1) DCH does not have a strong influence on the late-phase pressure trend, but only on the extent of the pressure peak at the bottom-head vessel failure; moreover the (conservative) further exchange of energy between entrained corium and containment gas (by the CORIUM module), which is modelled to occur, in ASTEC/case #2, immediately after the DCH pressure peak, shows a weak increase of containment pressure (Figure 1 shows that less than an extra pressurisation of 0.2 bar, that is the difference between the two ASTEC trends just after DCH and at the onset of MCCI, is predicted when the CORIUM option is "on");

2) water evaporation on the corium surface during the cavity flooding has an important influence on containment pressure requiring containment venting at an intermediate stage of the accident (2-4 days);

3) also sequences without cavity flooding require a containment venting, but at a late stage of the accident (5-10 days).

Moreover, the DCH pressure peak, because of its short duration, is not sufficient to challenge containment integrity/10/. DCH containment loading is plant specific, as it strongly depends on the reactor cavity configuration and the sub-compartment arrangement in the containment (an adequate sub-compartmentalization of the interface between cavity and containment has not been modelled here, therefore the exhibited trends in Figure 1 are largely conservative).

ASTEC sensitivity calculations/4/, /5/, /6/ and /7/ have shown that the maximum containment pressure, induced by DCH, is reduced to about 4 bar if the initial primary system pressure (driving pressure) is reduced from 160 to 80 bar. Therefore depressurisation of the primary system is a mitigation measure able to prevent DCH. Such a procedure has also the potential to prevent core melt by gaining access to low pressure water injection means; and if this is not successful, to delay core melt and to prevent high pressure melt ejection. However, a successful criterion should avoid a too early initiation of depressurisation, which will result in an additional loss of coolant inventory and in an early heat-up of the core.

A sequence without spray activation will require containment venting at about 50000 seconds (e.g. case #2 in Figure 1 shows that 5 bar are reached after 13-14 hours).
On the other hand, a sequence, even with large DCH impact, in which sprays are activated, exhibits a containment pressure always below 2 bar (at any time after DCH). However, the containment steam fraction will decrease at the beginning of spray operation (at this stage steam is condensing on spray droplets) and conditions for hydrogen combustion are met. Calculations (ASTEC/case #1 with "spray activation"/7/) show that up to 600 kg of H_2 can burn, just after the DCH peak, generating separate pressure peaks up to 3-4 bar) and increasing the risk to jeopardise the containment. Therefore, operators' mitigation actions should take this phenomenology into account when developing the best strategy for this accident sequence. For example, in the presence of a dry MCCI, operators might try to flood the cavity, for some time after the DCH, in order to inhibit to some extent H_2 combustion (steam fraction will increase again because of water evaporation on the corium surface). Calculations have shown that this is actually the case (in ASTEC/case #2 with "spray activation", less than 400 kg of H_2 have burned).

5 CONCLUSION

ASTECv0.3-calculated containment response to a TMLB sequence has been compared to MELCOR predictions for the Surry reactor: the comparison has shown that a good degree of confidence can be placed in ASTEC.
ASTEC & MELCOR have shown close predictions of the containment pressure once the late phase of the accident is reached: in fact all mechanisms, which may have contributed to the increase of pressure with a different timing, are, at this stage, close to their asymptotic limits.

Moreover, ASTEC sensitivity analyses have given insights on the most influencing factors and on accident management. For example, the analysis of a worst-case scenario has shown that a sequence involving a strong HPME (i.e. without implementation of a RCS depressurisation strategy), with cavity flooding and without intervention of sprays, as well as any hydrogen recombination feature, has a low probability to jeopardise the containment (a large dispersion of corium outside the cavity has also the beneficial effect to reduce the mass of corium involved in the MCCI), but requires a containment venting before 14-20 hours.
If the sump overflow into the cavity could be stopped at an intermediate stage of the accident, then containment venting is needed (essentially because of non-condensable gases generated by MCCI) between 4 and 10 days.

If the spray system could be available after the accident transient, its intervention would represent a strong mitigation action, but then particular attention should be devoted to its use in the closeness of the DCH event because conditions for hydrogen combustion could be met. In these circumstances, several pressure loads may occur in a short period of time almost overlapping with the DCH load and represent a risk for the integrity of the containment.
A possible trade-off might consist in delaying spray activation far enough from the HPME or, in case of a dry cavity, in allowing the flooding of the cavity, which would increase the containment steam fraction and inert the atmosphere. Afterwards, operators should use the spray in order to balance the pressure increase. In the late phase of the sequence, the cavity flooding would be beneficial also to limiting the extent of MCCI.

In any case, venting strategies should be adopted during the late phase of the accident, when mechanisms of retention of non-volatile FPs have taken place, also in order to reduce the content of hydrogen in the containment dome. The use of hydrogen recombiners would be very beneficial since they will significantly reduce the amount of burning H_2: optimizing recombiners' surface (to the O_2 content of the containment) roughly more than 50% of generated H_2 could be recombined.

ABBREVIATIONS

CSS	Containment Spray System
DCH	Direct Containment Heating
DF	(corium) Dispersal Fraction
ECCS	Emergency Core Cooling System
ESFs	Emergency Safety Features
FP	Fission Product
HPME	High Pressure Melt Ejection
LOCA	Loss of Coolant Accident
LOSP	Loss of Site Power
MCCI	Molten-Core Concrete Interaction
PORV	Pressurizer Power Operated Relief Valve
PRT	Pressurizer Relief Tank
PWR	Pressurized Water Reactor
RCS	Reactor Coolant System
SAMG	Severe Accident Management Guidelines
SG	Steam Generator
TMLB	Accident sequence (T "transient event, M "failure of the secondary system steam relief valves and the power conversion system", L "failure of the auxiliary feed-water system", B "failure of the electric power to ESFs").

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