Level 2 PSA - Comparison between classical and dynamic reliability methods. Specification and results of a benchmark exercise on consequences of hydrogen combustion during in-vessel core degradation.

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Abstract

During the second period of activity on level 2 PSA in the framework of SARNET, a simple exercise for application of dynamic reliability methods has been defined. This exercise concerns hydrogen combustion risk assessment in case of water injection during in-vessel core degradation for a French 900 MWe PWR. The following synthesis presents the SARNET partners solutions, which have been classified into five categories:

- *Direct calculation (Monte-Carlo simulations),*
- *Classical event tree method,*
- *Macro-event method with classical tools,*
- *Monte Carlo Dynamic Event Tree (MCDET),*
- *Stimulus-Driven Theory of Probabilistic Dynamics (SDTPD).*

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1. Introduction

In the ERMSAR-05 seminar, a summary was provided on the existing methods for accident sequence simulation based on reliability concepts [1]. Since this seminar, 10 partners of SARNET L2 PSA work package (AREVA, CEA, CSN, GRS, INR, IRSN, NEI, UJV, ULB, VEIKI) have applied different methods to a benchmark exercise relative hydrogen combustion risk assessment in case of water injection during in vessel core degradation for a French 900 MWe PWR.

The paper provides:

- a description of the benchmark exercise,
- a comparison of the different methods used by the partners,
- a presentation of obtained results,
- the lessons from the exercise and some perspectives for application of dynamic reliability methods in accident consequence analysis.

2. Presentation of the benchmark exercise

2.1. *Objectives*

The aim of the benchmark was to provide a “simple” example that demonstrates the limitation of classical event tree methods and the benefit of dynamic reliability methods.
The example was supposed to be quite “easy” to implement to limit as far as possible effort of SARNET participants. For that reason, the proposed problem is rather “analytical” and does not need a strong coupling between a severe accident code like ASTEC, MAAP or MELCOR and a dynamic reliability tool.
Nevertheless, two steps have been defined: the first step is the basic example with the modeling of three stochastic time-dependant events and the second step contains some additional assumptions relative to epistemic uncertainties.

2.2. *General description*

The benchmark exercise [2] is based on a hypothetical transient on a French 900 MWe PWR (3 loops, with Passive Autocatalytic Recombiners – PAR) which corresponds to the following scenario:

- loss of coolant accident (LOCA) after a 3’’ break size on cold leg of RCS,
- the safety injection system and Containment Heat Removal System (CHRS or spray system) are not available until the beginning of core dewatering,
- the steam generators are available but not used by the operators,
- no water injection occurs before core dewatering,

- the reactor is operating at nominal power before the initiating event.

The transient was previously calculated by IRSN for the 900 MWe level 2 PSA :

- with the SIPA (SCAR) simulator from the initiating event to the core dewatering,
- with ASTEC V0.4 from the core dewatering to vessel rupture.

The calculated core dewatering occurs at 4080 s (1h08mn). The vessel rupture occurs at 14220 s (3h57min) if no action is undertaken. Description of the transient is available in Table 1.

Time (second)	Event
4.080E+03	Start of core uncovery
4.125E+03	Start of cladding oxidation in the core
4.790E+03	Start of FPs release from fuel pellets
5.875E+03	Total core uncovery
6.035E+03	First fuel cladding rupture
9.360E+03	Melting pool formation in the core
1.068E+04	First lateral corium slump in vessel lower head
1.265E+04	Opening SG2 valves
1.266E+04	Closure SG2 valves
1.285E+04	Opening SG1 valves
1.286E+04	Opening SG3 valves
1.286E+04	Closure SG1 valves
1.287E+04	Closure SG3 valves
1.422E+04	Lower head vessel failure

Table 1 – Description of the transient

During the core degradation phase, the situation is supposed to be as follows:

- a water injection is available (with an “average” flow rate) and can be used by the operators,
- the spray system (CHRS) is available and can be used by the operators,
- water injection after the beginning of clad oxidation causes an increase of the hydrogen flow rate towards containment,
- hydrogen combustions can occur if the containment gas mixture is flammable; the recombiners, because of their high temperature, can initiate combustions; such combustions can be total (all the hydrogen in the containment is burnt) or not; the determination of the time of combustion is function of the state of flammability of the system, which is determined according to the containment atmosphere composition.

The main task of the benchmark was to quantify the risk of containment failure due to hydrogen combustion. This issue was supposed to be relevant for most level 2 PSA by the SARNET WP5 participants, although details in assumptions should strongly depend from the reactor.

2.3. *Specific assumptions*

Some specific assumptions have been proposed to define the stochastic event and the physical evolution of containment composition. These assumptions had the interest to avoid the use of a severe accident code. The table 2 (Appendix 1) describes these assumptions.

2.4. *Limitations*

The benchmark participants have discussed the limitations of these assumptions. The following points have been highlighted:

- events like water injection, spray system start, ignition of the H2-H20-air mixture by recombiners should no be considered as independent in a level 2 PSA,
- evolution of containment gas composition and temperature should be considered with more details (steam condensation on walls, impact of water in sump, impact of combustion on gas temperature, impact of water injection on steam mass),
- hydrogen distribution should not be considered as homogeneous in case of hydrogen production with a high kinetics,
- uncertainties should have to be considered on ignition criteria by recombiners.

Some of these limitations could only be solved by the coupling between a severe accident code (with detailed models) and a dynamic reliability tool. This is considered as a very interesting follow-up.

The main of interest of this benchmark concerns methodological aspects. Results should not be used for any other application.

3. Presentation of the partners solutions

3.1. Direct calculation

This method uses Monte Carlo simulations: all the random parameters are determined first, then the evolution of the system is calculated deterministically between 4080s (beginning of core dewatering) and 14220s (vessel rupture). At each second, the atmosphere composition, the temperature and the pressure are evaluated:

- if limit of flammability or ignition is exceeded, a delay of combustion is randomly sampled, and combustion is performed at the end of the delay;
- if a combustion occurs, the containment failure probability is calculated:
  - if the failure criterion is based on a containment pressure limit, the probability is equal to 1 if the containment pressure exceeds the pressure limit,
  - if the containment failure probability is a function of the pressure peak, the containment failure probability (CFP) associated with the simulation *i* is calculated by the following formula ($N_{comb}(i)$ is the number of combustions occurring during the simulation *i*):

$$CFP_i = 1 - \prod_{j=1}^{N_{Comb}(i)} \left(1 - CFP_j\right)$$

The final containment failure probability is obtained by the formula ($N_{simulation}$ is the total number of simulations):

$$CFP = \frac{1}{N_{simulation}} \sum_{i=1}^{N_{simulation}} CFP_i$$

This method has been used by INR and CEA and is quite simple to implement and validate in this case. The obtained results are considered as the reference results for the benchmark.
VEIKI also used this method as complementary calculation in order to calculate the containment failure probability for the step 2 of the benchmark.

3.2. “Classical” event tree methods

These so called “classical” methods are based on the event tree method. The probability of each binary node is obtained by dedicated studies. The time-dependent stochastic events cannot be implemented with this method and some additional (conservative) assumptions have to be defined. Some other assumptions have to be changed (for example calculation of the delay before combustion, no possibility of multiple combustions).
Because of these additional assumptions, these methods only allow to determine an approximation of the containment failure probability.
A solution has been proposed by AREVA, VEIKI and INR.

3.2.1. Solution proposed by VEIKI

This method is based on the method used by VEIKI for its level 2 PSA. The time of water injection and spray system activation are fixed at t=7000s. The containment atmosphere composition, pressure and temperature are calculated for different times in Excel data sheets. The overpressure after combustion is determined when the atmosphere is flammable (the assumptions regarding the fraction of hydrogen burnt and calculation of the overpressure after combustion are modified). This allows determining the ignition density function and the probability density function of the overpressure. Knowing the containment fragility density function, the containment failure probability can be calculated.
The different configurations of safety systems activation are calculated separately to affect the probability of the branching node in the following event-tree:

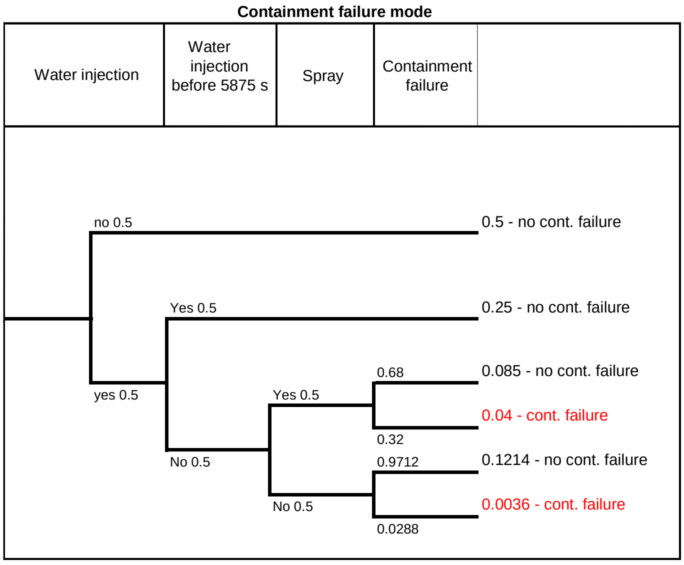

Figure 1 – Classical event tree method by VEIKI

3.2.2. Solution proposed by AREVA

Like for VEIKI, the pressure, temperature, and the containment atmosphere composition are calculated for different time steps. This work is done for different configurations of the safety systems (combination of 3 activation times for the spray system and the water injection) and allows estimating the containment failure probability for each case (a Monte-Carlo simulation is performed in order to determine the fraction of hydrogen burnt).
The cases with or without the safety systems are treated one by one and all the results are brought together in the following event-tree:

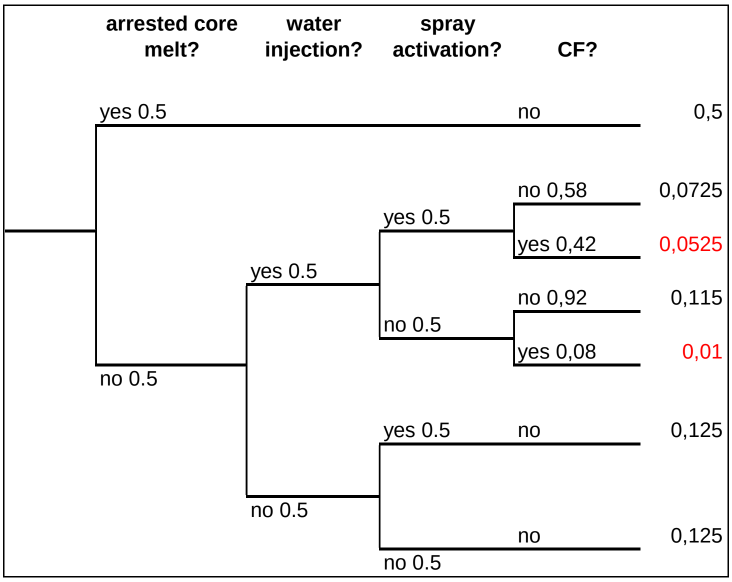

Figure 2 – Classical event tree method by AREVA

3.2.3. Solution proposed by INR

Like for VEIKI and AREVA, the pressure, temperature, and containment atmosphere composition are calculated for different time steps (169 time steps of 60s each). The flammability of the gas mixture is tested at each time step. For each time step, only the first combustion was taken into account. The multiple combustions were neglected.
For each time interval three questions were considered (figure 3):

- does hydrogen combustion occur at this time step?
- what is the fraction of hydrogen burnt?

- does the containment fail due to combustion?

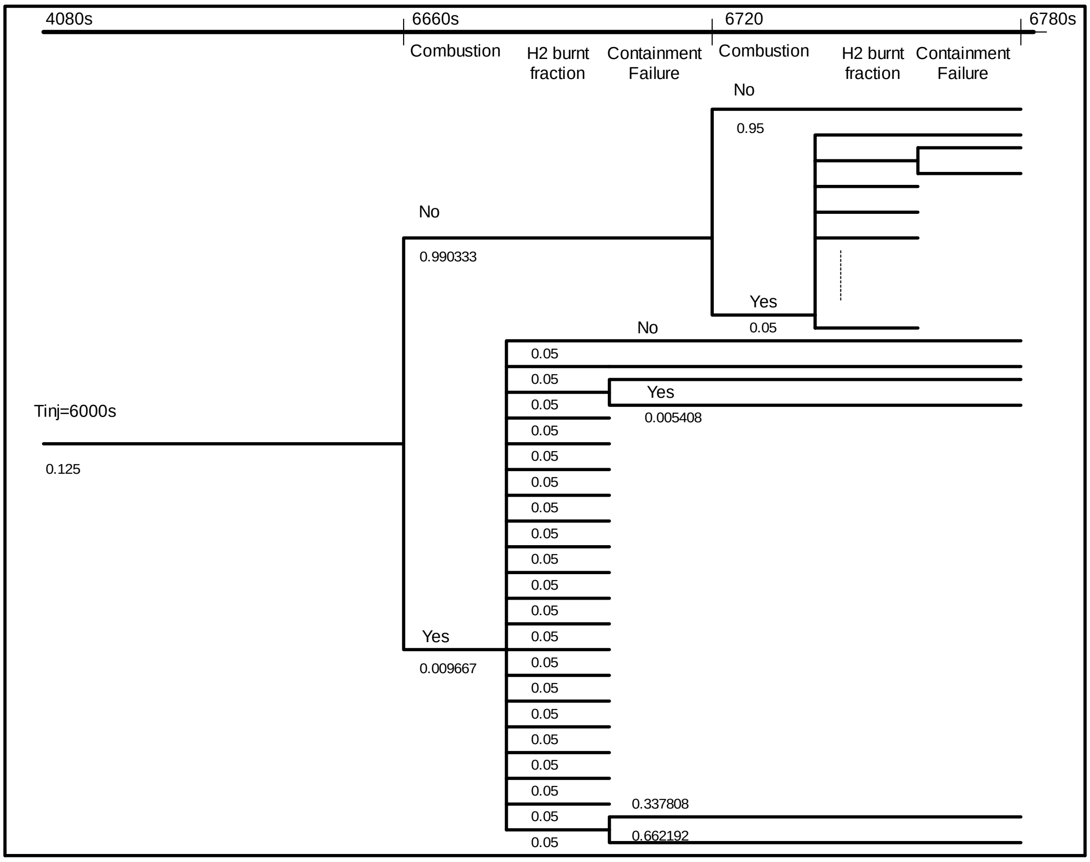

Figure 3 – Classical event tree method by INR

If the flammability limit is reached, the probability of hydrogen combustion is calculated using the delay before combustion determined following the benchmark specifications.
If the combustion occurs, the AICC pressure is calculated from PAICC function, for different fractions of hydrogen burnt (20 fixed fractions). The containment failure probability is calculated in function of AICC pressure.
The studies are done for four different deterministic configurations:

- CHRS and water injection are available (Tinj=6000s and Tspray=7000s): risk of containment failure,
- water injection only (Tinj=6000s, and spray system unavailable): risk of containment failure,
- CHRS and water injection do not work: the hydrogen concentration is under 4% and hydrogen ignition is not possible,
- CHRS works and water injection does not work: the combustion pressure is lower than the containment failure pressure limit.

It allows the calculation the global containment failure probability in a classical event-tree like in figures 1 and 2.

3.3. Macro-events method with classical tools

This method has been used by UJV and IRSN. The challenge was to use a classical L2 PSA tool (EVNTRE for UJV, and KANT for IRSN) and to take into account the dynamic aspect of the benchmark. The two solutions are based on the same idea: the division of the time of simulation in smaller time intervals covered by a unique event tree (called “triplet of questions” by UJV and “macro-event” by IRSN).

3.3.1. Solution proposed by UJV

Within the UJV method, 100 times of water injection and of spray system activation are used as sampling parameters and are generated by a random numbers generator. Other uncertainties like the time of ignition or the fraction of hydrogen burnt are treated by binning and making branches in the tree. Hydrogen burnt fraction follows a discrete distribution and leads to 20 branches in each time step in case of hydrogen ignition:

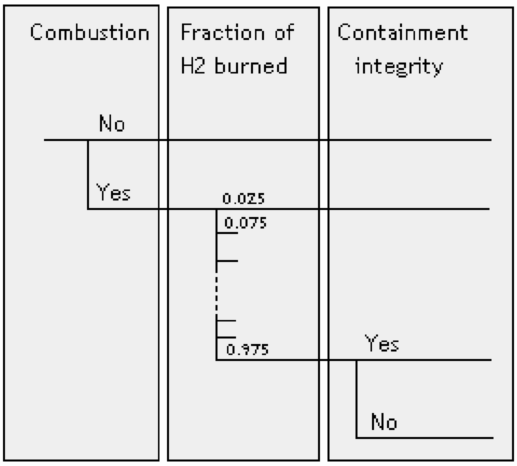

Figure 4 – UJV triplet of question

100 trees are generated for the 100 parameters sets for stochastic events. The mean number of branches is about 2.10^7, but it is very different for each case. The calculation time is 120 hours.
This method cannot be used for the step 2 of the benchmark because of the huge size of the trees and the prohibitive calculation time. Another approach using random sampling directly inside the trees evaluation is envisaged and should be realized before the end of SARNET.

3.3.2. Solution proposed by IRSN

In the solution proposed by IRSN, the macro event is duplicated for each time-step and the sum of all macro-event constitutes the global event-tree. The time interval covered by a macro-event is variable and function of the required precision. Indeed, before safety systems activation, there is no risk of combustion, so there is no need to use a small time step for calculation.

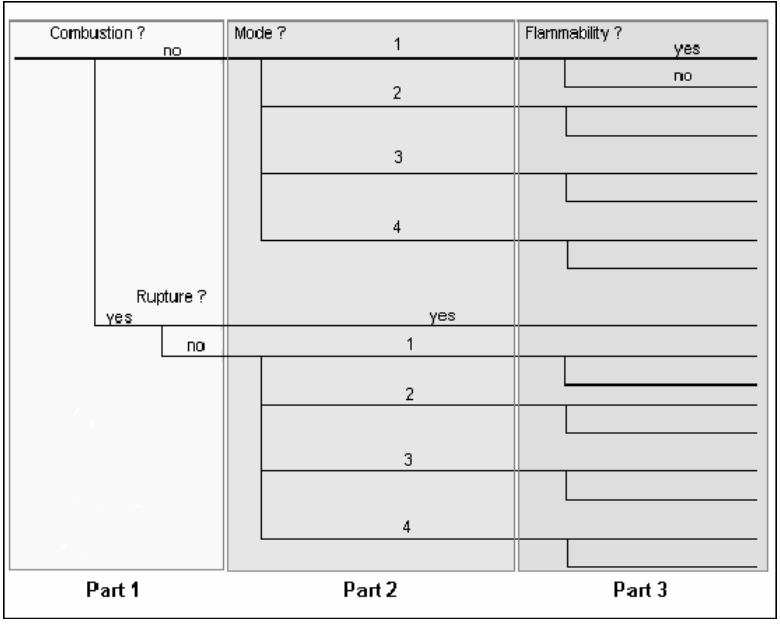

Figure 6 – IRSN macro-event

All assumptions have been taken into account, without any approximation except the choice of the time step. The KANT functionalities for programming calculation inside each the node of the event tree have been used. For example, the evolution of containment atmosphere composition is calculated and the fraction of H2 burnt is randomly sampled inside each macro-event.

For quantification of epistemic uncertainties, a double Monte-Carlo algorithm has been used after separation of stochastic events (water injection and spray system activation) and epistemic uncertainties (delay before combustion, fraction of hydrogen burnt for step 1). This separation allows the calculation of density probability function for the containment rupture, which represents the impact of the lack of knowledge on physical phenomena.

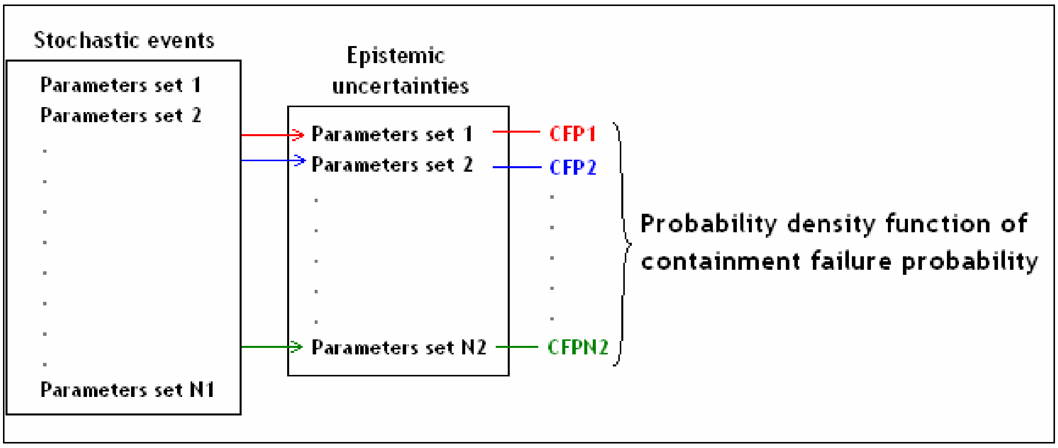

Figure 5 – IRSN treatment of the uncertainties

3.4. Monte Carlo Dynamic Event Tree (MCDET)

This method is developed and used by GRS. The MCDET method is based on the Monte Carlo method coupled with Discrete Dynamic Event Trees (DDET). Each DDET includes a number of sequences which arise from stochastic events considered within the DDET-structure. For the step 1 of the exercise, the stochastic events considered in the DDET are the safety systems activations and the fraction of burnt hydrogen (histogram distribution).

The following figure shows the DDET used for the step 1 of the benchmark exercise and the 22 sequences identified:

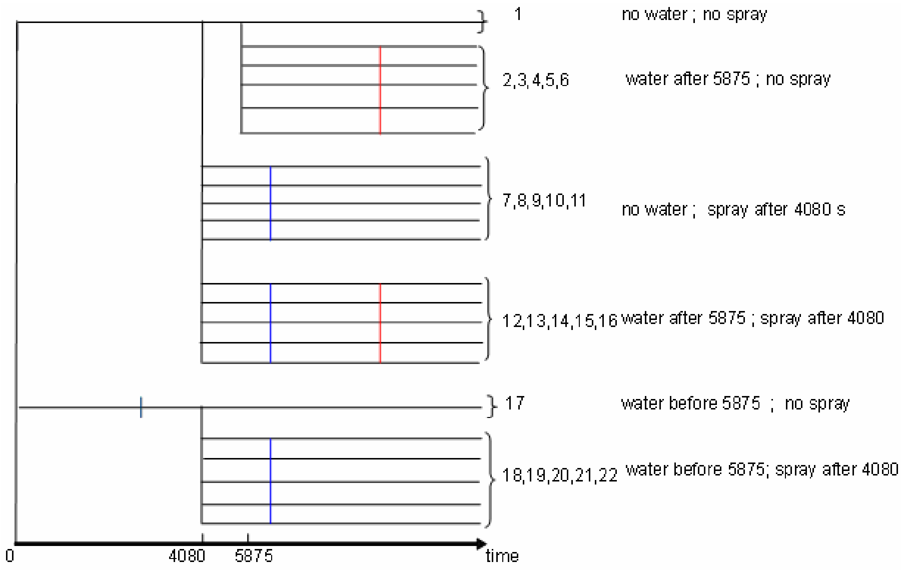

Figure 7 – Discrete Dynamic Event Tree

The other stochastic events are considered with Monte-Carlo simulation (time of safety systems activation, delays before combustion, fraction of hydrogen burnt).

For the step 2 of the benchmark, a different DDET is used. The stochastic events considered in DDET are safety systems availabilities and hydrogen flow rate. The uncertainties are considered with Monte-Carlo simulation.

3.5. *Stimulus-Driven Theory of Probabilistic Dynamics (SDTPD)*

This method is developed by ULB and also applied by LEI. The method is the same for both organisms with some differences in the application. The SDTPD is a general methodology used as a basis for a Monte Carlo simulation of dynamic reliability problems. For this benchmark exercise, a degraded form of the SDTPD is used, which quite close to a direct Monte Carlo solution of the problem.
The SDTPD analysis is based on a particular formalism:

- the "process variables" are the variables that describe the system evolution (6 variables for LEI and 9 variables for ULB)
- the "stimuli" are the events that can happen during the simulation (5 stimuli are defined by ULB and 6 by LEI)
- the "dynamics" are the different regimes of evolution of the continuous process variables.

The evolution of each process variable is defined for each dynamics.
To each stimulus are associated:

- a probability of activation and a probability of deactivation if needed,
- an activation (and if needed deactivation) delay.

This method allows a more precise modeling of combustion: if the flammability conditions change, combustion can be canceled. This point was not clearly specified in the specification of the benchmark exercise, but it shows one of the interesting capacities of the SDTPD.
A given number of histories (simulations) are performed. For each simulation, the final result is the containment integrity (saved or not). This allows determining the containment failure probability.

4. Results

The following paragraph shows the obtained results. These results are indicative and all differences between results have not been explained.

4.1. *Step 0 of the benchmark exercise*

All the assumptions are the same as for the step 1, except the assumption 18: if the pressure exceeds 0.5 MPa, the containment is supposed to fail.

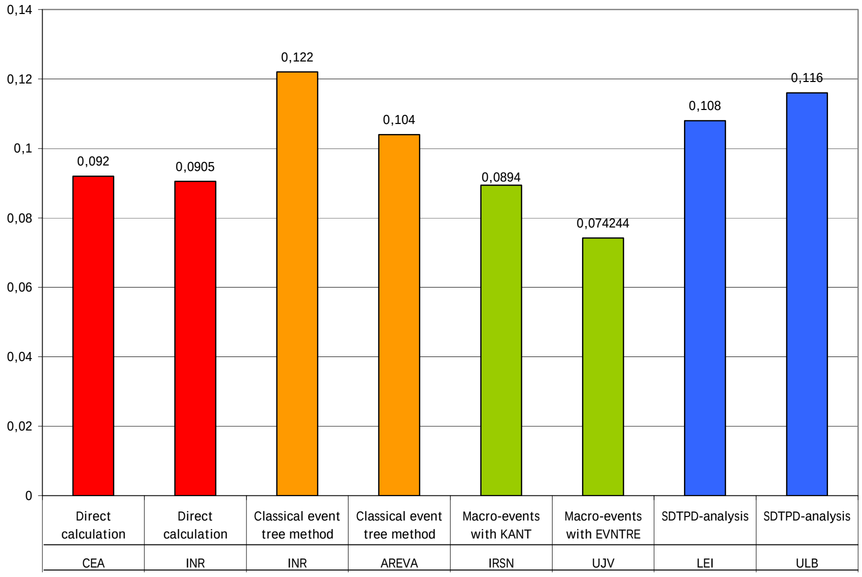

Figure 8 – Results for the step 0 of the benchmark exercise

The two results of the direct calculation method give almost the same results and can be considered as a reference results. The result found by IRSN is of the same order of magnitude. The UJV result is a little lower. The results found with the SDTPD method by ULB and LEI are of the same order of magnitude and a little higher than the reference result.

The results found by AREVA and INR with a classical event-tree method is just a little higher than the reference result. It confirms that the modified specification chosen by AREVA and INR in order to take into account the dynamic aspects of the benchmark (stochastic events) exercise are conservative.

4.2. Step 1 of the benchmark exercise

The only change between the step 1 and the step 0 is the calculation of the containment failure probability. For the step 1 the containment failure probability is function of the overpressure in containment.

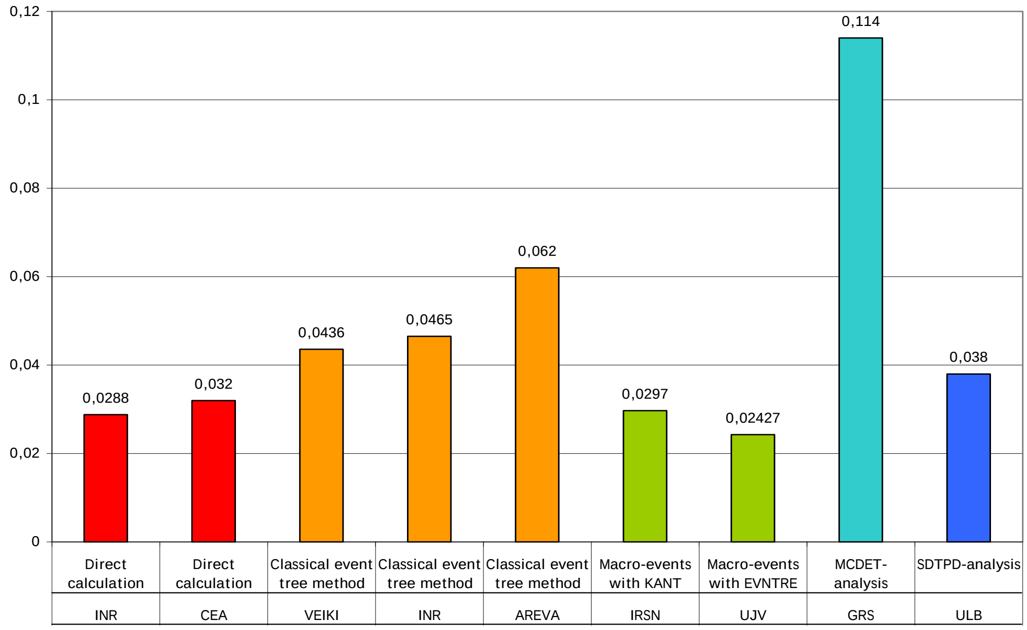

Figure 9 – Results for the step 1 of the benchmark exercise

The results found with the direct calculation method are almost the same (even if the result found by CEA is a little higher than the one found by INR), they can be considered as a reference.
Macro-events methods give here again almost the same results than the direct calculation methods, and as the ULB application of SDTPD-analysis.
As predicted, the classical event tree methods give a conservative result, which is higher for AREVA solution.
The MCDET solution gives a result much higher than the reference results, which should be due to a different interpretation of the specifications (this point has not been identified yet).

4.3. Step 2 of the benchmark exercise

For the step 2 of the benchmark, additional epistemic uncertainties are taken into account.

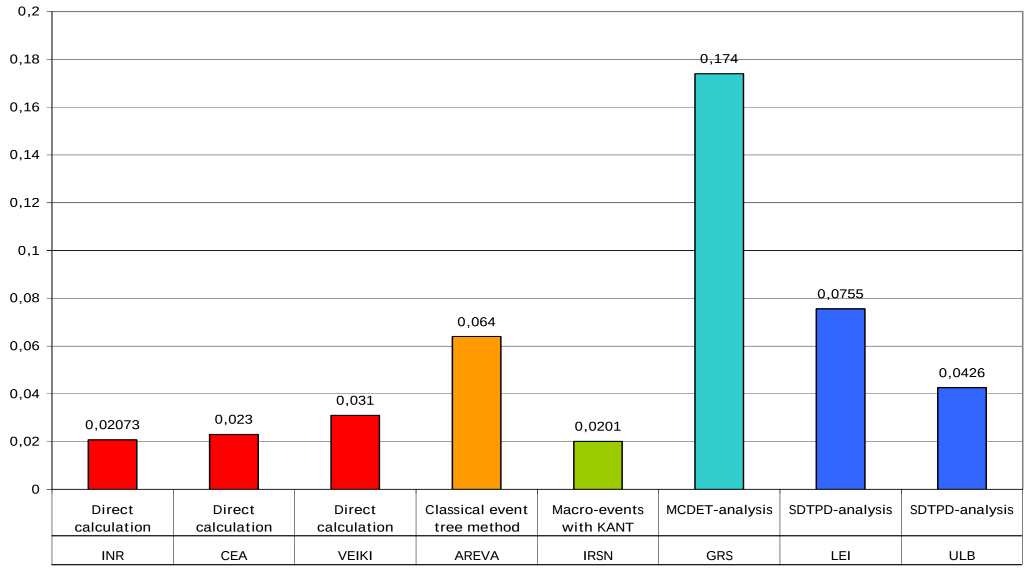

Figure 10 – Results for the step 2 of the benchmark exercise

Once again the two direct calculation method applications (CEA and INR) give almost the same results, and CEA result is a little higher. The direct calculation by VEIKI gives a result of the same order of magnitude and also the IRSN's macro-events method application.

The result found by GRS is higher for the step 2 than for the step 1, while it is decreasing for all the other calculations except for ULB solution. This could be revealing of a misinterpretation of the specifications.

The SDTPD-analysis by LEI gives a result three times higher than the reference result, while the ULB result is twice higher. As for the MCDET-analysis, the ULB result for step 2 is higher than for step 1.

The solution presented for AREVA does not take into account all the modifications. Only the containment failure probability, initial pressure, temperature and number of moles of H_2O are uncertain parameters.

5. Comments

5.1. Methods are operational

The first conclusion of this benchmark is the demonstration that some methods and tools are operational for dynamic reliability application. Solutions can be proposed with existing ("classical") tools or dedicated tools.

An important aspect is the CPU-time used by a solution. It must be taken into account in order to determine if a solution is really usable.
The CPU-time depends on many parameters like time step, number of Monte-Carlo simulation, or complexity of the event-tree as shown in table 2.

Method	Tree complexity	Time step of calculation (seconds)	Number of MC simulations	Total CPU-Time	Total CPU time for one MC sampling
GRS (MCDET)	Step 1: 22 branches Step 2: 6 or 10 branches	1	Step 1: 100 Step 2: 200	Step1: 1150 s	11,5 s
CEA (Direct	Direct calculation, 1 branch	1	10000	240 s	0,024 s

calculation)					
IRSN (Macro-events)	5 branches	Before safety systems activation : 200 After : 60	90000	7 h	0,28 s
UJV (Macro-events)	Varying Mean number of branches: **21250000**	60	100	120 h	1,2 h
ULB (SDTPD)	Direct calculation, 1 branch	100	100000	1800 s	0,018

Table 2 – Comparison of the CPU-time for different methods

The CPU-times related in the table are dependent of the computer configuration. The data given in the table should only be observed as an indication.

Except of for UJV's solution, where the CPU-time seems to be prohibitive, the CPU-times are reasonable and allows envisaging applications for more complex event-trees.

5.2. Treatment of the uncertainties

An interesting aspect of the benchmark is the quantification of both time-dependant stochastic events and epistemic uncertainties.

Treatment of uncertainties and post-processing of results has been treated in different ways:

- Direct calculation method: all the random parameters (epistemic uncertainties and stochastic events) are sampled for each simulation. Fractile 95% has been calculated by INR and represents both the lack of knowledge on physical phenomena and the random impact of system activation.
- UJV's macro-event method: stochastic events are sampled, and then the event-tree is simulated with probability of combustion when the containment atmosphere is flammable and branching for the determination of the fraction of hydrogen burnt. For the step 2 of the benchmark this method cannot be used, a different approach is required using the random sampling directly inside the tree calculation. This work will be done before the end of SARNET.
- IRSN's macro-event method: stochastic events and epistemic uncertainties are treated separately with a double Monte-Carlo simulation as presented in §2.3.2. This method allows calculation of fractiles that shows the influence of the uncertainties due to the "lack of knowledge".
- MCDET method: some uncertainties are considered in the discrete dynamic event tree structure (it is the case of systems availability), while others are considered with Monte Carlo simulation (it is the case of the instant of systems activation and epistemic uncertainties).
- SDTPD-analysis: Stochastic events are "stimuli" associated to a probability of activation and an activation delay, while the epistemic uncertainties are considered with Monte-Carlo simulation.
- Classical method: Stochastic events become deterministic. The epistemic uncertainties are considered with Monte-Carlo simulation when it is possible.

IRSN has provided the calculation of the probability density function of the containment failure probability:

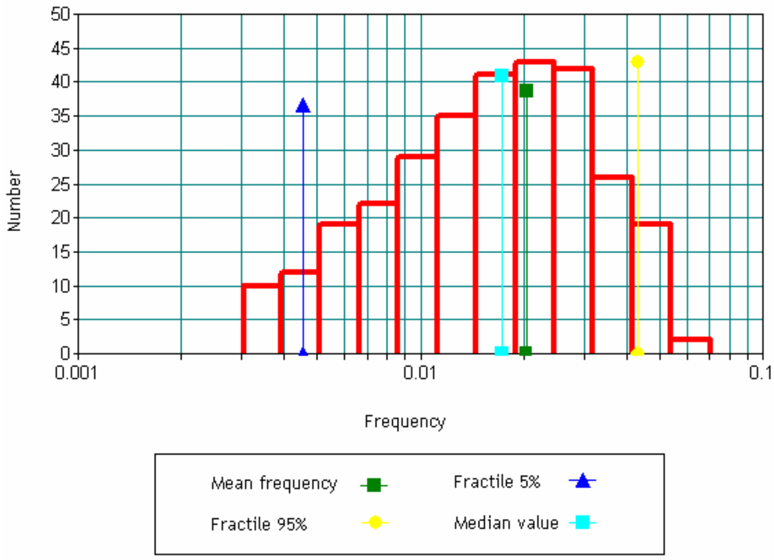

Figure 12 – Probability density function of the containment failure probability, IRSN step 2

ULB has also treated separately the uncertainties, as shown on the figure 13.

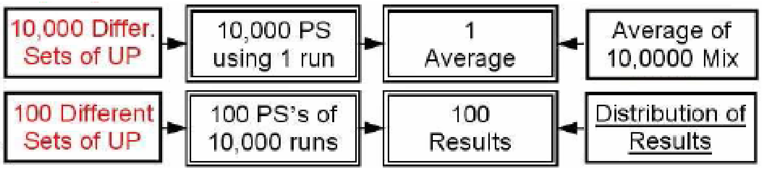

Figure 13 – Treatment of the uncertainties by ULB

When 100 probabilistic simulations (PS) with 10000 histories are done for 100 different sets of uncertain parameters (UP), it gives the distribution of the containment failure probability. The following figure shows the frequencies of combustions and ruptures for 100 simulations, for the step 2 of the benchmark exercise:

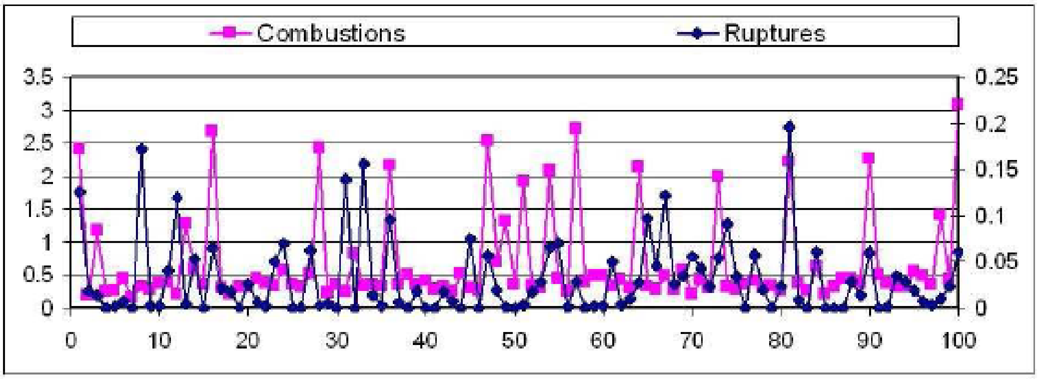

Figure 14 – Ruptures and combustions frequencies for 100 simulations, ULB step 2

GRS and INR have provided a confidence interval for the calculation (GRS and INR):

	Mean value	Confidence interval 95%
Step 1	0.114	[0.11 ; 0.12]
Step 2	0.174	[0.156 ; 0.192]

Table 3 – Confidence intervals for the GRS results

	Mean value	Confidence interval 90%
Step 1	0.02821	[0.027348 ; 0.029071]
Step 2	0.02073	[0.020211 ; 0.021248]

Table 4 – Confidence intervals for the INR results

UJV provides uncertainties that reflect only lost branches due to the selected cutoff frequency:

	Mean value	Uncertainties
Step 1	0.024276	± 0.0022329

Table 5 – Confidence interval for the UJV results

The comparison of the different approaches for the treatment of uncertainties shows that different methodological approaches can be proposed and also different post-processing possibilities.

5.3. Follow-up applications

The benchmark has been defined for a specific transient of the French 900 MWe PWR. Other examples could be easily defined for other reactors and other transients.

Such a demarche could be proposed for examination of the robustness of severe accident guide with a more detailed assessment than only a full-scope L2 PSA. Such applications constitute an interesting outlook for dynamic reliability methods.

Some guidance for uncertainties analysis in connection with dynamic reliability method should be an interesting follow-up of the benchmark.

6. Conclusion

The aim of this benchmark exercise was to compare the advantages and inconveniences of the existing methods used for the treatment of dynamic reliability problems.

The methods used by the participants have been classified in five categories:

- Direct calculation (Monte-Carlo simulations),
- Classical event tree method,
- Macro-event method with classical tools,
- Monte Carlo Dynamic Event Tree (MCDET),
- Stimulus-Driven Theory of Probabilistic Dynamics (SDTPD).

The following conclusions can be proposed for each method:

- the direct calculation method is the simplest way to obtain correct results for this dynamic reliability problem, and the validation is very easy; unfortunately, such a method would not be relevant for a more complex L2 PSA event tree,
- the classical event-tree methods, which suppose additional assumptions, give results with the same order of magnitude than the reference results but depending from how the additional assumptions are implemented. The benchmark exercise is a very simple case, but we can suppose that such approximations in a more complex model could lead to a result very far from reality. The validation of the results obtained with these methods is quite difficult: assumptions that cannot be implemented because of the limits of the method must be interpreted, and this interpretation must be done in order to preserve the coherence of the final result,

- concerning the “macro-events with classical L2 PSA tools” method, the solutions developed by UJV and IRSN show that classical tools can be used if they are flexible (possibility of implementation of physical modeling in the event-tree nodes). The use of macro-event allows taking into account time-dependant stochastic events. The IRSN’s solution presents the advantage of providing the probability density function of the containment failure probability, by considering separately the stochastic events and the epistemic uncertainties with a double Monte Carlo simulation,
- MCDET: the MCDET method uses a very interesting approach with consideration of the uncertainties either with DDET or with Monte-Carlo simulation, allowing distinction between epistemic and stochastic uncertainties. Nevertheless the results found are very far from the reference results. In order to correctly evaluate this method, the differences in the result will have to be explained.
- SDTPD: like the MCDET method, the SDTPD-analysis uses an interesting approach that allows taking into account the specificities of the dynamic reliability problems. SDTPD-analysis gives formalism for the treatment of such problems, but for the moment this method does not give correct results for step 2. Different applications of this method do not give the same results. Developments of the method and of the associated tools are still in progress but the application to the benchmark provides encouraging results.

To conclude, these results are an encouragement to continue the development of specific methods for dynamic reliability problems, including specific post-processing of results, particularly for uncertainties analysis.

Some of the participants have proposed the definition of a step 3 for the benchmark exercise, which should contain more realistic and detailed assumptions, in order to highlight the benefits of dedicated methods. This step 3 could include a coupling with a severe accident code like ASTEC. The specifications of this new benchmark exercise have to be discussed between the participants.

7. Acknowledgement

Authors would like to acknowledge all participants to this benchmark for their valuable contributions, and all useful technical discussion. Detailed presentations of the solutions are available in the document in reference [3].

8. Reference

1. SARNET – Conference ERMSAR 2005 – Aix-en-Provence – France - Accident simulation methods based on dynamic reliability concepts. P.E Labeau
2. SARNET work package 5.3 – Level 2 PSA - Specification of a benchmark exercise relative to hydrogen combustion for application of dynamic reliability methods - IRSN/DSR/SAGR/FT.2005-154 - SARNET PSA2-P12 – E. Raimond
3. SARNET work package 5.3 – Level 2 PSA - Synthesis of a benchmark exercise relative to hydrogen combustion for application of dynamic reliability methods - IRSN/DSR/SAGR/FT.2005-154 - SARNET PSA2-P12 – T. Durin, E. Raimond, R. Alzbutas, A. Catana, J. Dienstbier, G. Dirksen, T. Eimontas, J. Eyink, P.-E. Labeau, G. Lajtha, H.Löffler, M. Marques, E.-M. Pauli, A. Peeters, J.Peschke, G. Radu, Z. Téchy

9. Appendix – specific assumptions of the benchmark

N°	Step 1	Step 2
1	No evolution of containment gaseous phase composition except for hydrogen before spray activation. Initial containment gaseous phase composition provided from ASTEC results.	Idem but uncertainties have been defined for initial containment phase composition.
2	Hydrogen flow rate in containment without water injection has been extracted from ASTEC results (Figure 1 & 2).	Idem with uncertainties on hydrogen flow rate in containment.
3	Between total core uncovery (at 5875s) and lower head failure (at 14 755s) all injected water is supposed to participate in the oxidation of Zr and steel ; the increase of the flow rate of hydrogen is supposed to be equal to 3 tons/hour (0.833 kg/s)	Between total core uncovery (at 5875s) and 7000s : 40% of the step 1 rate with probability 0.3, 50% with probability 0.4 and 60% with probability 0.3. Before formation of melting pool (9400s): between 0.416 kg/s and 0.833 kg/s (uniform distribution) Before lower head failure: 40% of the step 1 rate (0.333 kg/s), with probability 0.3, 50% with probability 0.4 and 60% of the above rate with probability 0.3.
4	The maximum H_2 produced mass is equal to 950 kg (oxidation of Zr and steel)	
5	The total H2 mass flow rate is the sum of ASTEC source term and increase due to water injection	The total H2 mass flow rate is the sum of ASTEC source term and increase due to water injection
6	A specific table provides the decrease of steam in containment due to spray system activation (from ASTEC result)	Idem with uncertainties on the kinetics of steam condensation after spray system activation
7	A specific table provides the decrease of temperature in containment due to spray system activation (from ASTEC result)	Idem with uncertainties on the kinetics of temperature decrease after spray system activation
8	A specific table provides the decrease of pressure in containment due to spray system activation (from ASTEC result)	Idem with uncertainties on the kinetics of pressure decrease after spray system activation
9	Pressure peak due to combustion is calculated by a PAICC routine in function of the average temperature of gas in containment (°C), the total pressure in containment (bar),the molar fraction of steam, the molar fraction of hydrogen, the molar fraction of oxygen and the molar fraction of nitrogen	
10	A specific correlation provides the mass flow rate of hydrogen recombined by the PAR system	Idem with uncertainties on specific coefficient of the correlation
11	Heterogeneity of the hydrogen distribution in the containment is not taken into account.	
12	A specific correlation (Shapiro limit) provides the limit for inflammability of containment gaseous phase in terms of %H2 versus %H20.	
13	A specific correlation provides a limit above which the inflammation of containment gaseous phase by the hot parts of PAR system is certain.	
14	A specific correlation provides an estimation of delay before hydrogen combustion in function of hydrogen concentration.	
15	An aleatory function provides the fraction of burnt hydrogen after a combustion	Idem but the function depends on the hydrogen concentration
16	The probability that water injection is available between total core uncovery (5875s) and vessel rupture (14220s) is 0.5. The time when water injection starts is uniformly distributed between total core uncovery and vessel rupture.	Idem but the probability of the availability of water injection follows a discrete distribution
17	The probability that the spray system can be activated after core uncovery (4080 s) and before vessel rupture is equal to 0.5. If the spray system can be activated, the time when spray system is activated is uniformly distributed between core uncovery (4080s) and vessel rupture.	Idem but the probability of the availability of spray system activation follows a discrete distribution
18	Assumption relative to containment : Step 0 : the containment will be first supposed to fail if overpressurization due to hydrogen combustion exceeds value 0.5 MPa Step 1: a more realistic assumption for containment with a containment failure probability in function of pressure peak.	the containment failure probabilities law of step 1 is be multiplied by a common factor between 0.5 and 1.5 (uniform distribution) to take into account uncertainties
19	No automatic spray system activation is considered.	Automatic spray system may be taken into account as a sensivity study.

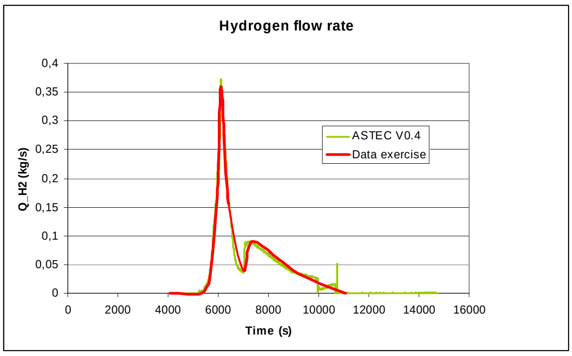

Figure 1. – Hydrogen flow rate

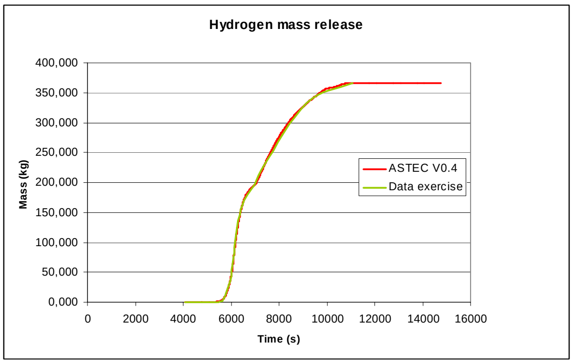

Figure 2. – Hydrogen production (cumulated mass)