Tractebel's Hydrogen Risk Analyzer : A tool to assess the loads and risks associated to hydrogen combustion inside nuclear buildings

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Abstract : The hydrogen risk assessment performed in the frame of the Belgian level 2 PSA is supported by a dedicated tool developed by Tractebel : the Hydrogen Risk Analyzer (H2RA). The H2RA tool is coded in Python and takes as inputs thermodynamics conditions provided by MELCOR supporting calculations for the building of interest e.g. the containment. By computing the loads due to a hydrogen combustion (deflagration, detonation) and comparing them to fragility curves, the H2RA tool is then able to ultimately output the probability of building failure for the considered accident sequence.

Keywords : PSA, Hydrogen risk, PWR.

1. CONTEXT AND OBJECTIVE OF THE HYDROGEN RISK ANALYZER

All Belgian nuclear units have been equipped with passive autocatalytic recombiners inside the reactor building around 1990 in order to mitigate the risk of a hydrogen combustion during a nuclear accident with core damage.

Although such system is passive and highly reliable, an assessment of the loads and risks associated to a hydrogen combustion is desirable in the frame of the Level 2 PSA for the Belgian units. To perform this assessment, Tractebel has developed a tool called the Hydrogen Risk Analyzer (H2RA).

For Belgian plants, PSA level 2 models exist and are represented by a large event tree modelled using the EVNTRE [1] software. To support the quantification of this event tree, plant-specific MELCOR 1.8.6 [2] supporting calculations are performed.

These supporting calculations can provide the time-dependent evolution of hydrogen concentration within each modelled volume of the containment or auxiliary building. There is also the possibility to compute pressure loads associated to hydrogen combustion by using the BURN package included within MELCOR. However, this option is not used in Tractebel in the PSA frame because the BURN package within MELCOR is based on the HECTR [3] code and considers ignition as soon as the gas concentrations reach a pre-defined criterion. Moreover, the package does not allow computing loads due to flame acceleration (FA) or detonation and could therefore provide non-best estimate results.

Consequently, the H2RA tool was developed to assess the hydrogen risk using a probabilistic approach (probability of having an ignition source, of flame propagation, ...) and taking into account flame acceleration and detonation potential thanks to inputs from MELCOR supporting calculations.

Note that no comparison of the analysis performed by the H2RA tool against other existing methodologies has been performed. However, one straightforward benefit of the H2RA is that it provides a quantitative analysis of the hydrogen risk rather than using common PSA conservative assumptions e.g. containment failure under detonation conditions.

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2. DESCRIPTION OF THE HYDROGEN RISK ANALYZER

2.1. Complete workflow

The complete workflow is provided in appendix A.

2.2. Inputs

The H2RA tool is coded in Python and takes as inputs thermodynamics conditions (gas concentrations, pressure, temperature) provided by MELCOR supporting calculations for the building of interest e.g. all control volumes belonging to the containment. For each MELCOR timestep and each MELCOR control volume, one therefore obtains the following data :

Time	Pressure	Temperature	x_{H_2O}	x_{H_2}	x_{CO}	x_{O_2}	x_{N_2}	$x_{C_{O_2}}$
[seconds]	[bara]	[K]	[-]	[-]	[-]	[-]	[-]	[-]

2.3. Combustion regime

The first step is to define the conditions for a control volume to present a combustion risk. Three regimes are analysed : deflagration, flame acceleration (FA) and deflagration to detonation transition (DDT). Diffusion burns and direct detonation are not analysed because the former is assumed to have negligible impact on the pressurisation and the latter is highly unlikely to occur.

Then, the tool defines the following set of deflagration conditions :

— $x_f > x_f^{min}$,
— $x_{O_2} > 5v\%$,
— $x_i < 60v\%$.

with

— $x_f = x_{H_2} + x_{CO}$
— $x_i = x_{H_20} + x_{CO_2}$

Similarly, the tool defines the following set of criteria for flame acceleration (FA) :

— Criteria for deflagration must be met,
— $x_f > 10v\%$,
— $\sigma_{index} = \frac{\sigma(x_f, x_i, x_{O2}, T)}{(\sigma_{crit}(x_f, x_i, T)} > 1$

Where σ and σ_{crit} are polynomial functions of the molar fractions and temperature Eventually, a final set of criteria for Deflagration To Detonation (DDT) is defined :

— Criteria for deflagration must be met,
— $D > 7\lambda$

Where D is a characteristic length specific to each volume and λ is the detonation cell width and is a function of the volume temperature, pressure and combustible gas and inertant fractions (X_f, X_i). All criteria given hereabove are based on reference [4].

2.4. Combustion sequences

At this point, the H2RA tool can provide the user the possible mode of combustion for each MELCOR control volume at each MELCOR time step.

However, this only indicates the **susceptibility** of a control volume to burn. For an actual burn to occur, an ignition source must be present. Furthermore, propagation of the flame can occur between control volumes. These uncertainties make it impossible to determine only one time-evolving combustion scenario for the considered accident sequence. Rather, multiple combustion scenarios are possible. In the H2RA nomenclature, one speaks about combustion sequences and subsequences.

The **combustion sequences** are constructed by analysing the combustion conditions in all control volumes. One combustion sequence is constructed as soon as the conditions change in at least one control volume. The construction of sequences is illustrated in Figure fig :sequences for two control volumes. The information about all sequences is stored within a Panda dataframe (Python structure).

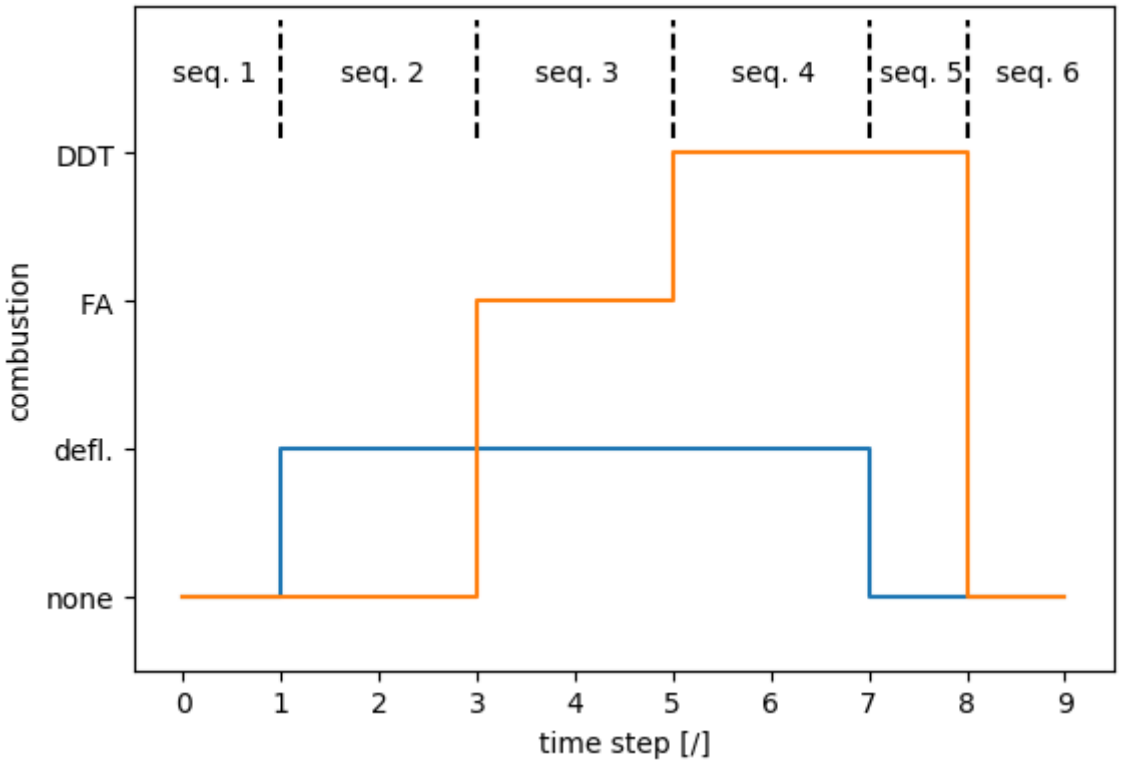

FIGURE 1: construction of combustion sequences

Along with the combustion sequences, a memory tracks for each control volume the timespan during which the volume features flammable condition. Indeed, in the probabilistic treatment, the longer a control volume exhibits flammable conditions, the more probable the burn is. This is illustrated in Figure 2.

One now has a dataframe containing all combustion sequences defined by a specific set of combustion modes for all the control volumes.

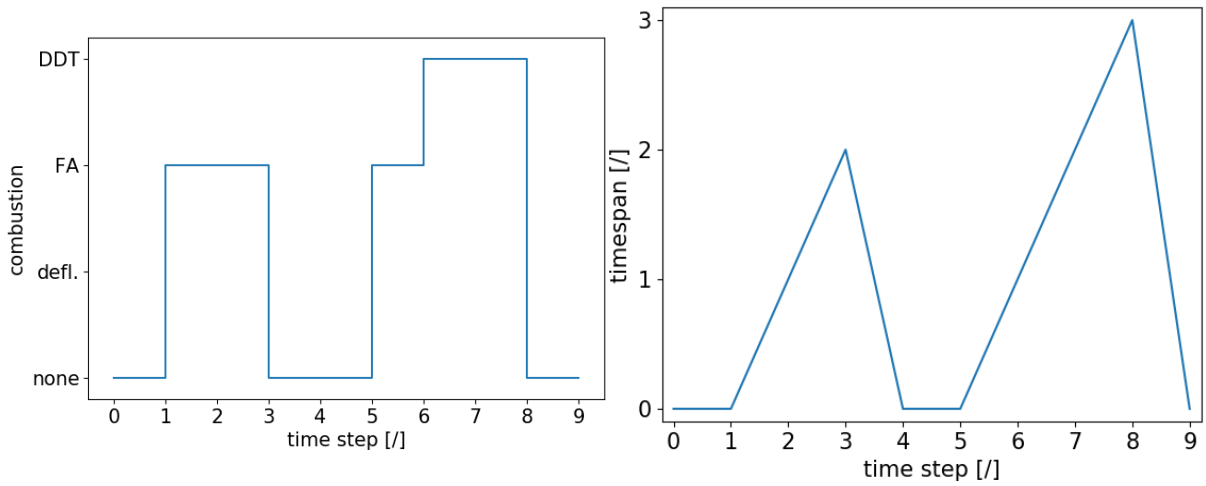

FIGURE 2: Graphical illustration of the memory tracking the timespan during which a control volume exhibits flammable conditions.

It is however not guaranteed that the identified combustion mode actually occurs in each control volume. **Combustion subsequences** are therefore created from combustion sequences to account for all possibilities. If N denotes the number of control volumes in a certain sequence that meet the conditions of any combustion type, then this sequence has 2N-1 subsequences neglecting the subsequence where no combustion occurs. A dataframe is constructed containing the information about the subsequences.

Two last actions are performed on the subsequences dataframe.

The first action is performed to incorporate the concept of ignition time cap, denoted H (see Figure 4). To incorporate this concept, the dataframe is transformed in such a way that subsequences whose durations (tracked thanks to the memory explained further above) exceed H are handled appropriately (i.e. cut at the timing of certain ignition) and subsequences following one where ignition was certain to occur are deleted.

The second action is performed to ignore subsequences where connectivity criterion is not met. In other words, subsequences where multiple CVs are assumed to burn must answer a connectivity criterion to be considered possible. Otherwhise, it is assumed that the probability of this subsequence to occur is negligible and it is therefore discarded. The connectivity criterion is illustrated in Figure 3. The subsequence on the left answers the connectivity criterion while the one on the right does not and would be discarded. Indeed, for the left subsequence, all control volumes featuring burnable conditions are connected without a ”buffer” of control volumes featuring non-burnable conditions. The opposite situation is featured for the right sequence since CV2, CV3 and CV4 featuring burnable conditions are buffered by CV4 and CV5 featuring non-burnable conditions.

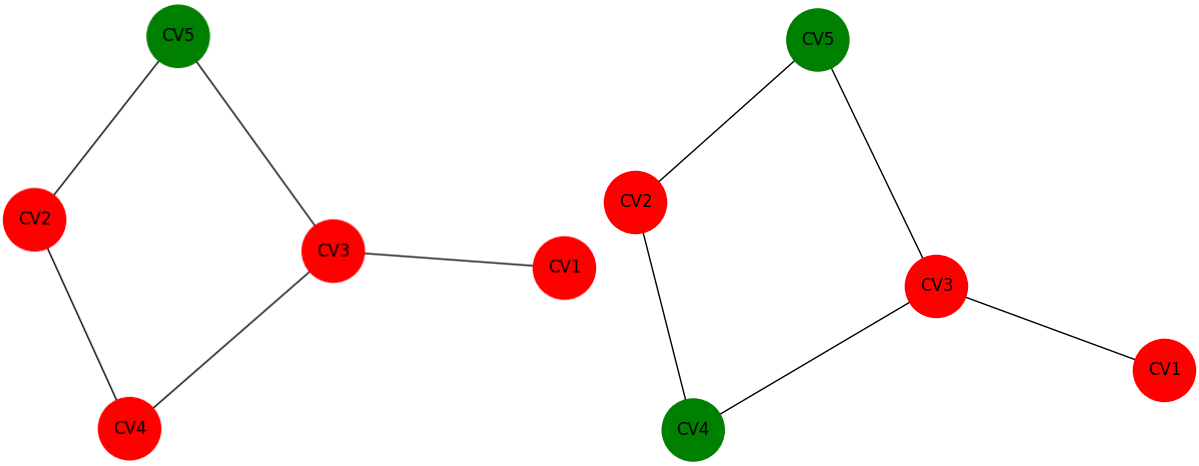

FIGURE 3: Illustration of the desired connectivity of the control volumes in a subsequence. Red means the control volume features burnable conditions. Green means the control volume does not.

2.5. Pressure loads

At this point, all information regarding possible combustion subsequences is gathered in one dataframe. The next step is to calculate the pressure load caused by a (hypothethical at this point) burn in each control volume and at each time step. The pressure load caused by the burn is assumed to be the Adiabatic Isochoric Complete Combustion pressure (PAICC) but takes into account a combustion completeness factor in case stoichiometric burn is impossible. The pressure load is then time-averaged for each CV in each subsequence :

$$P_{CV} = \frac{1}{t_{end} - t_{start}} \int_{t_{start}}^{t_{end}} P_{CV}(t)dt$$

2.6. Probability for a subsequence to occur

The next step in the analysis is to compute the probability that a subsequence actually occurs. Beforehand, one additional hypothesis is made regarding the subsequences : actual ignition only takes place in one control volume.

This hypothesis was already hinted when one defined the concept of flame propagation. This hypothesis is added for computational simplification. Indeed, take one subsequence where three control volumes feature combustible conditions. Then the following combinations are possible :

- Actual ignition in CV1, CV2 and CV3
- Actual ignition in CV1 and propagation to CV2 and CV3
- Actual ignition in CV2 and propagation to CV1 and CV3
- Actual ignition in CV3 and propagation to CV1 and CV2
- Actual ignition in CV1 and CV2, propagation to CV3
- Actual ignition in CV1 and CV3, propagation to CV2
- Actual ignition in CV2 and CV3, propagation to CV1

This produces 7 subsequences. Obviously, for more than 3 volumes, the complexity increases even more. It was therefore decided to limit the possibilities by constraining each subsequence to have

one actual ignition and then propagation. At this point, probabilistic considerations are introduced in the H2RA tool. The first one is the probability to have an ignition source during a subsequence (p_{source}). This probability depends on one hand on the availability of an Alternative Current (AC) source during the scenario (dependent on the sequence being analysed e.g. CSBO) and on the other hand on the presence of a hotspot (hot piping, hot melt, ...) in a control volume and is determined via expert judgment.

Next is the probability linked to the time to ignition. Indeed, even if an ignition source is present, it is assumed that ignition can be delayed or avoided. Therefore, a probability p_{time} is introduced via expert judgment and is determined by the definition of a flammable timespan H. p_{time} is illustrated in Figure 4.

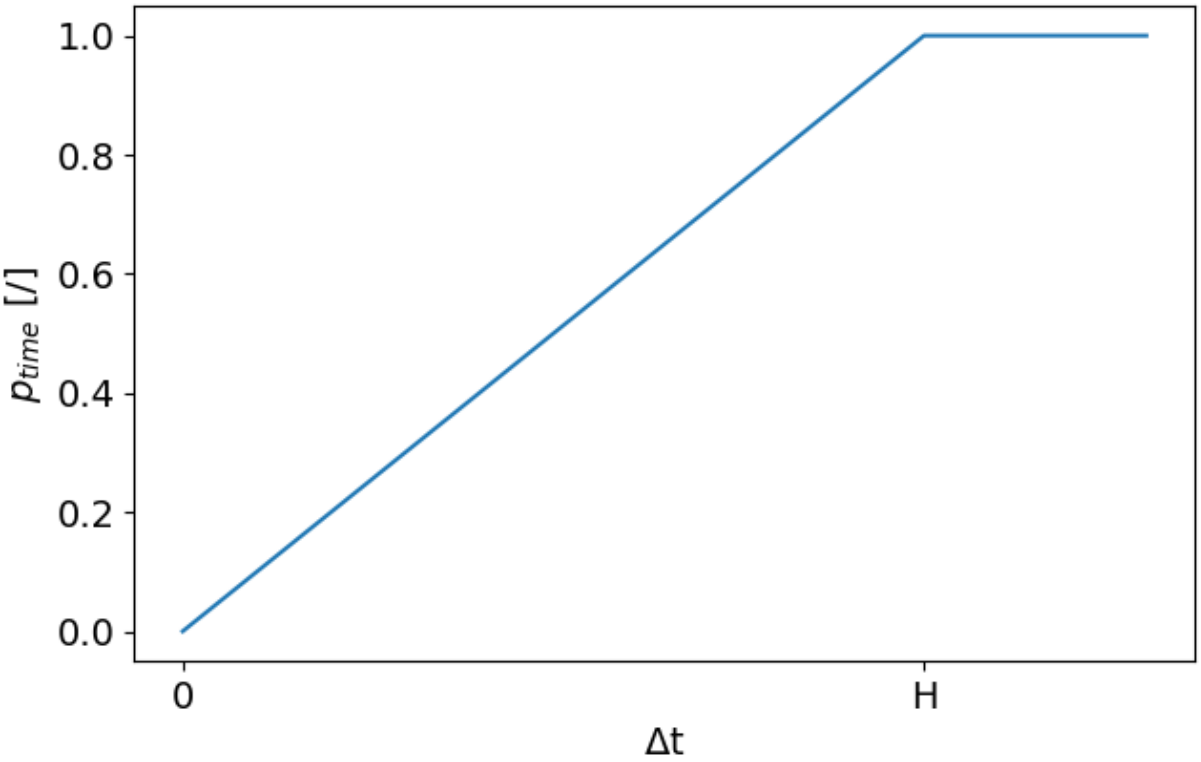

FIGURE 4: Graphical illustration of the concept of p_{time} and H.

The third introduced probability is the propagation probability. It is once again determined by expert judgment and is a function of the combustion type and the number of connected control volumes. It is unit specific as it depends on the geometry. Note that these three probabilities depend on the considered control volumes. Given the assumption on the subsequences, the three probabilities are computed for each combusting CV in each subsequence and are then averaged. This computes the probability that a subsequence k occurs (p_{occ_k})

2.7. Monte carlo simulation for FA and DDT

Eventually, probabilities are introduced regarding the pressure load scaling factors for Flame Acceleration (FA) and Deflagration to Detonation Transition (DDT). These probabilities were again evaluated by expert judgment and result in a probability distribution. Therefore, a Monte Carlo simulation is ran for each subsequence and the average over all simulation (p_{load_k}) is taken as the result

for the subsequence.

2.8. Final computation

Multiplying p_{load_k} by p_{occ_k}, one obtains the probability that a subsequence k fails the considered building. Remembering that all subsequences are in fact only possibilities for one same sequence, only one subsequence can remain. Conservatively, the subsequence featuring the highest failure probability is kept. Summing over all sequences, one finally obtains the probability that the considered MELCOR calculation fails the considered building (P_{final}).

Repeating the process for several MELCOR calculations, one can then quantify the probability that a certain type of sequence (LOCA, ISLOCA, ...) fails the containment or the auxiliary building. Specific severe accidents phenomena can be taken into account to distinguish even more the possible MELCOR scenarios (e.g. safety injection recovery involving increase hydrogen production).

3. CONCLUSION

For each representative Belgian unit undergoing a level 2 PSA, a detailed hydrogen risk assessment is performed thanks to the Hydrogen Risk Analyzer developed by Tractebel. This tool makes use of the containment fragility curves and of the plant-specific detailed MELCOR supporting calculations and is based on well-known combustion criteria.

Following the detailed hydrogen risk assessment of each representative Belgian unit, the conclusion is that the risk of a hydrogen combustion occuring in the Belgian plants and failing the containment is extremely unlikely as expected due to the presence of the numerous Passive Autocatalytic Recombiners (PARs) installed during the 90's.

Acknowledgements

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References

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