# MELCOR ANALYSIS OF EARLY CONTAINMENT VENTING RISK IN A SEVERE ACCIDENT SCENARIO OF BOILING WATER REACTOR

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**ABSTRACT**

This paper presents a MELCOR assessment for early containment venting risk during severe accidents of a Nordic boiling water reactor (BWR). The study was motivated by the recent analyses of the MAAP4 and MELCOR 1.8.5 codes for the BWR, which predicted that the containment venting was activated at quite different times, and the earlier actuation might result in overdose of fission products release into the environment. Since the containment venting was triggered by the containment pressure limit (set-point) whose estimate is affected by many phenomena and modeling parameters in the simulations, a MELCOR sensitivity analysis was performed to find out the most influential parameters in predicting the containment venting event. To account for the latest development of the code, MELCOR 2.1 was used in the present work. The new calculation once again indicated that the early containment venting did not occur if the parameters' settings referred to the recommendations of the MELCOR Best Practices. However, the sensitivity study revealed that the decay heat plays a key role in containment pressurization, and the containment venting might be activated if the ANS decay heat correlation was employed. It was also found that the hydrogen production during the ex-vessel fuel coolant interactions could accelerate the containment pressurization process.

**KEYWORDS**
Severe accident, containment thermal-hydraulics, MELCOR code, simulation

## 1. INTRODUCTION

The containment filtered venting system (CFVS) has been widely implemented in Nordic nuclear power plants, as an important severe accident mitigation measure to prevent containment from overpressure. Although the radioactive release dose can be largely reduced through the CFVS, there is still some fission products release to the environment. A recent comparison between the MAAP4 and MELCOR1.8.5 analyses for the same SBO scenario of a Nordic boiling water reactor (BWR) indicated that there was a significant difference between the times of containment venting actuation. As shown in Fig. 1, the MAAP4 simulation had a quicker pressure build-up in the containment which subsequently triggered an earlier containment venting after about *4 hours*, far before the recovery of the containment spray system at *8 hour*. However, the containment venting did not occur in the MELCOR1.8.5 simulation due to the slower containment pressure build-up process and the recovery of the containment spray after *8 hours*.

Since the containment venting is triggered by the containment pressure limit (a set point) whose estimate is affected by many phenomena and modeling parameters in the simulation, there is a clear need to perform a sensitivity analysis to understand the uncertainty in predicting the containment venting event. For this purpose, the MELCOR 2.1 code [1] was used as the simulation vehicle for a station blackout (SBO) scenario of the reactor with 1000 *MW* electric power rating. First, a reference case was defined to reflect the MELCOR Best Practices [2] as well as the plant data consistent with the MAAP input. Then, the severe accident phenomena which may pressurize the containment are analyzed so as to identify the sensitivity parameters in their models and correlations. Finally, based on important phenomena and the matrix of the sensitivity parameters, an extensive sensitivity analysis was carried out to investigate the influences of the phenomena and parameters on the pressurization and possible containment venting. The results did not only help understand the risk of early containment venting, but also provided insights on modeling development needs for the early containment venting issue.

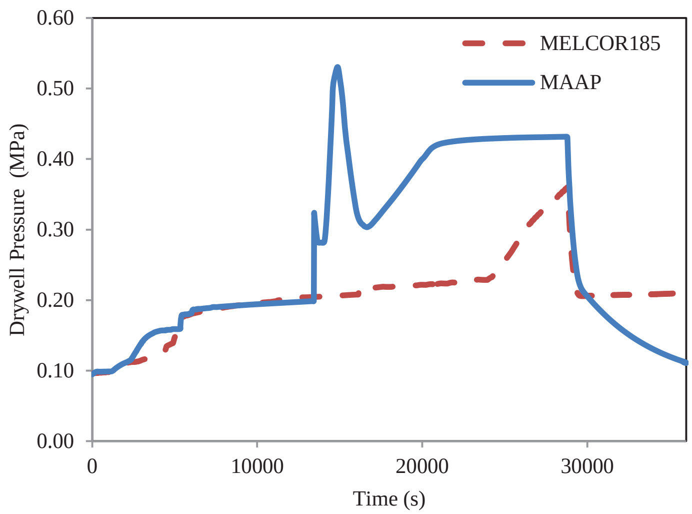


*Figure 1: Comparison of containment pressures in MAAP4 and MELCOR185 simulations.*

## 2. REFERENCE MODEL

### 2.1 Description of the BWR Plant

The reactor chosen in the present study is a typical Nordic boiling water reactor at the power capacity of *1000 MWe*, equipped with internal recirculation pumps. A number of various safety systems had been installed as safety measures, according to the design principle of diversity and redundancy. In the present analysis for the SBO accident, the Emergency Core Cooling System (ECCS) is unavailable, while the other safety systems are assumed to be intact or operate as follows:

- Automatic Depressurization System (ADS), which was activated 10 *minutes* after the signal of the low water level in the vessel, i.e., *0.5 m* above the top of core.
- Pressure Suppression (PS) system, i.e., the steam condensation system, which is an inherently passive system designed to limit the containment pressure. The steam is discharged through the blowdown pipes into the wetwell pool where it is condensed. The Vacuum Breakers between the wetwell and the drywell ensure that the wetwell pressure will not be higher than that in the drywell.
- Containment Filtered Venting System (CFVS), which was activated when the containment pressure was higher than *0.53 MPa*.
- Containment Spray System, which was unavailable during the first *8 hours* in the SBO accident, but will be recovered afterward.
- Cavity Flooding System, which was activated 30 *minutes* after the signal of the low water level in the vessel, i.e., *0.5 m* above the core exit.

### 2.2 MELCOR Modeling and Nodalization

A reference MELCOR 2.1 model is established according to the MELCOR Best Practices [2] by which only the gross creep rupture is considered as the vessel failure mechanism. The plant data (such as core geometry and mass, in-vessel water inventory, compartments' volumes, heat structures in the vessel and in the containment, etc.) used in the reference model is scrutinized together with engineers from the BWR plant, referring to the MAAP4 input and the plant data.

Fig. 2 shows the containment nodalization in the reference model. The containment comprises 5 volumes, representing the upper drywell, lower drywell, wetwell, blowdown pipes and overflow pipes separately. Two volumes are used to simulate the CFVS scrubber, with one additional volume for the environment. The vessel breach is represented by Flowpath-700, which will open when the vessel failure occurs. Among other flow paths, Flowpath-362 is used for modeling the containment filtered venting pipe, and Flowpath-205 is for the cavity flooding system.

The MELCOR thermal-hydraulic nodalization of the vessel is illustrated in Fig. 3. The core was modeled by 5 radial rings in the core region with additional two control volumes in the lower and upper plenums, respectively. Flowpath-314 is used for modeling the ADS system.

In the reference model, the default modeling parameters of the MELCOR 2.1 code are chosen, except for those recommended by the MELCOR Best Practices [2] as listed in Table I.

*Table I: Best-estimate parameters and values.*

| Category | Parameters | Value in Best Practices [2] | Default value | Note |
|---|---|---|---|---|
| Properties | MLT-UO2 (*K*) | 2800 | 3113 | Melting temperature decrease due to eutectics |
| | MLT-ZrO2 (*K*) | 2800 | 2990 | |
| Fuel rod failure and collapse | SC1131(2) (*K*) | 2400 | 2400 | Molten Zr 'breaks out' from ZrO2 shell at 2400 K |
| | SC1132(1) (*K*) | 2800 | 2500 | Fuel rod collapse temperature |
| | Cladding failure criteria* | Cladding failure(CF) function | Cladding temperature | Fuel assembly failure and convert to particulate debris bed |
| Core degradation | DHYPD in core (m) | 0.01 | 0.01 | Characteristic debris size |
| | DHYPD in LP (m) | 0.02 | 0.02 | |
| Debris heat transfer in lower plenum & Penetration failure | VFALL (*m/s*) | 0.01 | 0.1 | Effective fall velocity into the lower plenum |
| | PORDP | 0.4 | 0.25 | Porosity of particulate debris |
| | HDBH2O [$W/(m^2.K)$] | 2000 | 100 | Heat transfer coefficient between debris and water |
| | HDBPN [$W/(m^2.K)$] | 100 | 1000 | Heat transfer coefficient between debris and penetration |
| | HDBLH [$W/(m^2.K)$] | 100 | 1000 | Heat transfer coefficient between debris and lower head |
| | TPFAIL,(*K*) | 9999 | 1273 | Penetration failure temperature |
| Cavity Heat Transfer | EMISS.OX | 0.9 | 0.6 | Emissivity of oxide, metallic, and surrounding materials |

*The cladding failure function is used for modeling the cumulative damage state of standing fuel assembly. [2]

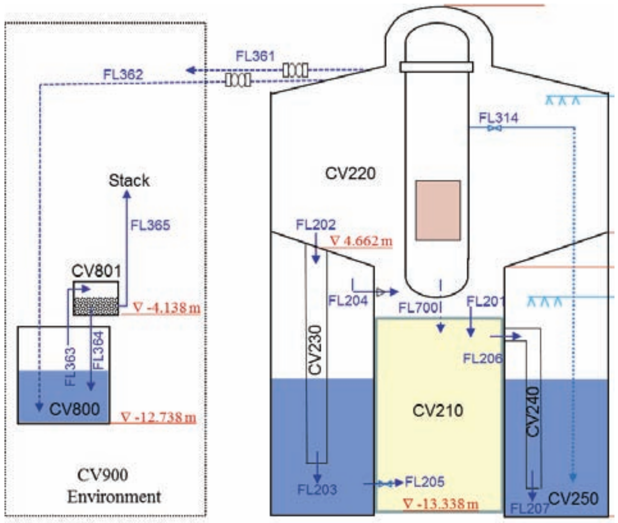


Figure 2: Containment nodalization.

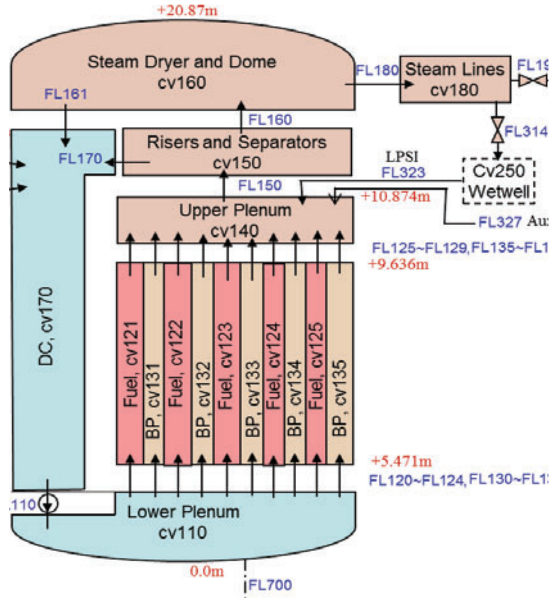


Figure 3: Vessel nodalization.

## 3. IMPORTANT PHENOMENA AND SENSITIVITY PARAMETERS

### 3.1 Phenomena Important to Containment Pressure

The containment venting depends on the containment pressure buildup process. The mass and energy release is the driving force of the pressurization, such as steam produced in the vessel or in the cavity due to decay heat power, as well as non-condensable gases generated by the oxidization of fuel cladding and stainless steel or by the molten core concrete interaction (MCCI) in the reactor cavity. Thus, the following phenomena are important to the containment venting:

- In-vessel hydrogen production.
- Non-condensable gases generation due to MCCI.
- Steam generation in the containment.
- Ex-vessel hydrogen production due to FCI.
- Decay heating.

### 3.2 Selection of Parameters for Sensitivity Study

Based on the reference model, some MELCOR modeling parameters for the important phenomena mentioned above are chosen to perform the sensitivity study, with the objectives to find out the most influential parameters on the containment pressurization and to identify the probable range of containment venting time in the SBO accident scenario.

*In-vessel hydrogen production*

As shown in the uncertainty analysis using MELCOR 1.8.5 for the in-vessel hydrogen production during a SBO accident [3], there were a lot of parameters affecting the core degradation and cladding oxidation. Here, only the cladding failure function and the fuel rod collapse temperature are investigated in the sensitivity analysis since their default settings are different from those in the MELCOR Best Practices [2].

The default value of the fuel rod collapse temperature is 2500 *K*, but it was assigned as 2800 *K* in MELCOR Best Practices [2], which also suggests the cladding failure function for predicting the standing fuel rods collapse (forming particulate debris). A cumulative damage function related to the cladding temperature is defined, which is not used in the default settings of the MELCOR code.

*Non-condensable gas generation due to MCCI*

After the debris arrives at the floor of the reactor cavity, there is simultaneous heat transfer from the debris to both the overlying water pool and the bottom concrete. If there is inadequate heat transfer to cool the debris, the debris will ablate the concrete and release non-condensable gases. Otherwise, the debris is cooled down below the concrete ablation temperature, and the molten core concrete interaction (MCCI) will be terminated, disabling the production of non-condensable gases. The MACE experiment [4] and CCI tests [5] show that cracking of the crust with water ingression and multi-dimensional effects greatly enhanced the debris coolability when water was present. If a 10 times of the default heat transfer coefficient is employed in the MCCI modeling of MELCOR, the experiment is predicted well by the code. Thus, the convective heat transfer between the corium and overlying water and the conductive heat transfer within the corium are considered in the present sensitivity study by assigning different multipliers to the heat transfer coefficients.

*Steam generation in the containment*

After the vessel failure, the corium will slump into the cavity, heat up the water, and then generate steam. The steam production consists of two parts, i.e. the steam generated by the sensible heat of the corium, and the steam produced by the decay heat. The former one mainly depends on the amount of the released corium and its temperature, while the later one is influenced by the vessel failure time. They are both related to the in-vessel accident propagation process. Since the core degradation has been discussed above, the debris behavior in the lower plenum and the vessel failure are focused here.

As mentioned above, in the MELCOR Best Practices [2], only the gross creep rupture is considered as the vessel failure mechanism, by referring to the SNL LHF tests [6] in which the gross creep rupture of the lower head was identified as the most likely vessel failure mode. However, the penetration failure may be an important failure mode for the vessel of a boiling water reactor due to the forest of control rod guide tubes and instrument tubes on the lower head. Nevertheless, since the modeling of penetration in MELCOR 2.1 is rather simple, it is hard to get a good prediction about the penetration failure time. To account for the possible uncertainty when activating the penetration failure modeling for the BWR, the following parameters are chosen as sensitivity parameters: the mass of the penetration, the heat transfer coefficients between the debris and the penetration/vessel lower head.

For the debris behavior in the lower plenum and the penetration failure, the effective fall velocity, porosity of particulate debris, the heat transfer coefficient between debris and water, are selected as sensitivity parameters.

*Ex-vessel hydrogen production*

Following the vessel melt-through, fuel coolant interaction (FCI) occurs in the wet cavity. During the FCI, the un-oxidized zirconium in the corium can be oxidized by water/steam, generating the hydrogen. Moreover, it was found that $UO_2$-$ZrO_2$ melt may solidify during the FCI and forms a $U_{1-x}Zr_xO_{2+y}$ solid solution, leading to release of a small amount of hydrogen during this process [7]. According to the ZREX experiment [8], up to 26% of metallic zirconium was oxidized during the FCI in the case of no steam explosion.

In the present analysis, the Lower Pressure Melt Ejection (LPME) model in the MELCOR FDI package is chosen for dealing with the FCI process, thanks to the activation of the ADS system. However, the LPME model does not consider oxidation of the ejected debris. In order to investigate the impact of the FCI oxidation on the containment pressurization process, external hydrogen and heat sources are introduced into the cavity for modeling the zirconium-water interaction. Since steam explosion is not modeled in present analysis, the maximum zirconium oxidized fraction is considered as 26%.

*Decay heating*

Since the decay heat is the main driving force of the severe accident propagation, two different approximations calculated by the correlations ANS and the ORIGEN, are used in the sensitivity study. It should be mentioned that the total decay heat power depends on the plant operation time and fuel reloading scheme, which could generate the uncertainty.

### 3.3 Calculation Cases

In summary, the calculations of the sensitivity study are divided into 8 groups as shown in Table II, for investigating the effects of decay heating, MCCI and the core degradation. In each group, 18 cases are dedicated to the parameters' sensitivity of debris heat transfer and penetration failure in the lower head, as listed in Table III.

Moreover, 5 variations of the reference model are defined to investigate the effects of the FCI oxidation and the decay heat on containment pressurization.

- REF: the reference model using the MELCOR Best Practices [2], without modeling of oxidization during ex-vessel FCI and penetration failure, using ORIGEN decay heat correlation.
- VAR1: a variation of the reference model using ANS decay heat correlation.
- VAR2: a variation of the reference model with 26% zirconium oxidized during ex-vessel FCI.
- VAR3: a variation of the reference model with 10% zirconium oxidized during ex-vessel FCI.
- VAR4: a variation of VAR2 using ANS decay heat correlation.
- VAR5: a variation of VAR3 using ANS decay heat correlation.

*Table II: Sensitivity analysis groups.*

| Group | Decay heat correlation | Cavity heat transfer enhancing factor | Cladding failure function |
|---|---|---|---|
| 1 | ORIGEN | 10 | Yes |
| 2 | ORIGEN | 10 | None |
| 3 | ORIGEN | 1 | Yes |
| 4 | ORIGEN | 1 | None |
| 5 | ANS | 10 | Yes |
| 6 | ANS | 10 | None |
| 7 | ANS | 1 | Yes |
| 8 | ANS | 1 | None |

*Table III: Sensitivity parameters related to vessel failure time.*

| Case | VFALL* | HDBH2O | PORDP | HDBPN | HDBLH | Penetration mass multiplication |
|---|---|---|---|---|---|---|
| C1 | 1 | 100 | 0.25 | 1000 | 1000 | 1 |
| C2 | 0.7 | 500 | 0.28 | 800 | 800 | 1 |
| C3 | 0.3 | 900 | 0.31 | 600 | 600 | 1 |
| C4 | 0.16 | 1300 | 0.34 | 400 | 400 | 1 |
| C5 | 0.04 | 1700 | 0.37 | 200 | 200 | 1 |
| C6 | 0.01 | 2000 | 0.4 | 100 | 100 | 1 |
| C7 | 1 | 100 | 0.25 | 1000 | 1000 | 0.1 |
| C8 | 0.7 | 500 | 0.28 | 800 | 800 | 0.1 |
| C9 | 0.3 | 900 | 0.31 | 600 | 600 | 0.1 |
| C10 | 0.16 | 1300 | 0.34 | 400 | 400 | 0.1 |
| C11 | 0.04 | 1700 | 0.37 | 200 | 200 | 0.1 |
| C12 | 0.01 | 2000 | 0.4 | 100 | 100 | 0.1 |
| C13 | 1 | 100 | 0.25 | 1000 | 1000 | 10 |
| C14 | 0.7 | 500 | 0.28 | 800 | 800 | 10 |
| C15 | 0.3 | 900 | 0.31 | 600 | 600 | 10 |
| C16 | 0.16 | 1300 | 0.34 | 400 | 400 | 10 |
| C17 | 0.04 | 1700 | 0.37 | 200 | 200 | 10 |
| C18 | 0.01 | 2000 | 0.4 | 100 | 100 | 10 |

* Definitions of the parameters are listed in Table I.

## 4. CALCULATION RESULTS AND DISCUSSIONS

As illustrated in Fig. 4, the histories of the containment pressure had wide variations among the different simulation cases. In some cases the containment pressure buildup process was so slow that the containment venting was not triggered at all since the containment spray alone activated at 8 hour was sufficient to suppress the containment pressure. However, in the other cases, the containment venting was needed to prevent the containment overpressure, i.e., below the containment capacity of 0.53 *MPa* before the spray system was recovered at 8 hr. Fig. 5 shows that the cases of VAR4, VAR5 and some of Group 5 through Group8 had the early containment venting. Since those cases all used the ANS decay heat correlation, one can concluded that the higher decay power in the simulations played a key role in the early containment venting.

The history of the containment pressure for any case could be roughly divided into 4 phases according to the different kinds of mass and energy release sources which contributed to the containment pressurization. The first phase is related to the steam discharge from the vessel to the wetwell through the ADS which was activated at around 0.45 hour for all the simulated cases. Since the steam was mostly contained in the wetwell through direction contact condensation, the containment pressure increased just slightly (about 0.02 MPa).

The second phase is related to the melt relocation and debris quench as well as the in-vessel hydrogen generation, starting from the same time (around 0.7 hour) but ending differently due to varied core meltdown process and melt progression. As shown in Fig. 6, the in-vessel hydrogen production ranged from 300 *kg* to 700 *kg*, corresponding to the containment pressure from 0.18 *MPa* to 0.25 *MPa* at the end of this second phase (see Fig. 4).

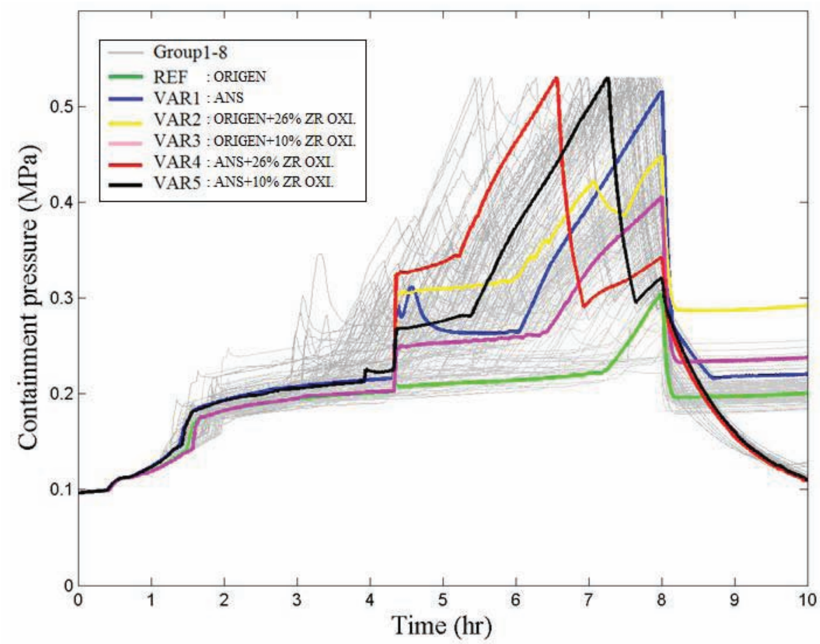


*Figure 4: Containment pressure transients.*

The third phase is related to the slump of the core debris from the lower head into the cavity after the vessel failure. This phase was characterized by rapid release of steam and hydrogen produced during the subsequent fuel coolant interactions (FCI). The MELCOR has a very simple model to estimate the steam production due to heat transfer from the debris to the water, but does not consider the hydrogen generation.

As an attempt to account for the impact of the oxidation of the metallic components during the FCI, two different amounts of hydrogen (referring to 26% and 10% ex-vessel zirconium oxidization) were directly added to the cases of VAR2 through VAR5 though the Tabular Function of MELCOR, as shown in Fig. 7. By comparing the REF case with its variations VAR2 and VAR3 in which about 500 *kg* and 200 *kg* hydrogen were introduced separately, it is obvious that the addition of the hydrogen caused a significant rise in the containment pressure, as shown in Fig. 4. Thus, the hydrogen production during the FCI may lead to the early containment venting as observed in the cases VAR4 and VAR5 whereas the containment venting did not occur in the case VAR1.

The fourth phase is related to the corium interactions with coolant and concrete on the floor of the cavity, producing steam and non-condensable gases. As shown in Fig. 8, the molten core concrete interaction (MCCI) did not occur in the cases using the enhanced heat transfer coefficient for cooling debris which was recommended by the MELCOR Best Practices [2]. If the cooling heat transfer coefficient was not enhanced, the MCCI might occur and non-condensable gases could be produced, as in some cases of Group3, Group4, Group7, and Group8. The steam production rate in the cavity depends on the decay power. Since the ANS correlation predicts a higher decay power than the ORIGEN correlation, more steam was produced in the ANS cases than the ORIGEN cases (see Fig. 9).

Finally, the containment venting time is illustrated in Fig. 10. In summary, for most cases using the ANS decay power correlation, the containment venting was activated between 5.5 hr and 8 hr to avoid the overpressure, while for the cases using the ORIGEN decay power correlation the containment venting was not needed since the pressure could be solely suppressed by the containment spray.

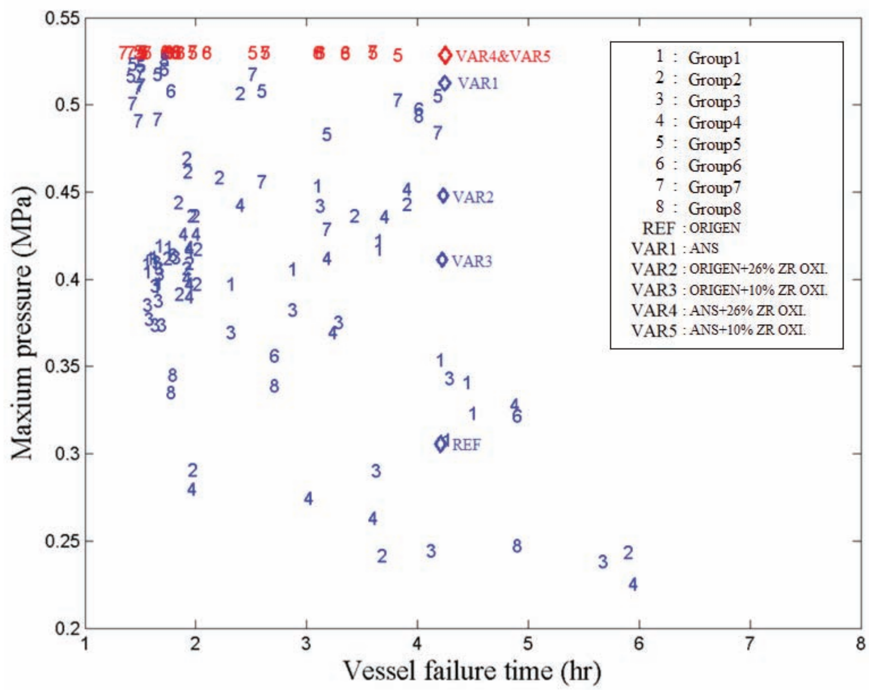


*Figure 5: Vessel failure time and the maximum containment pressure.*

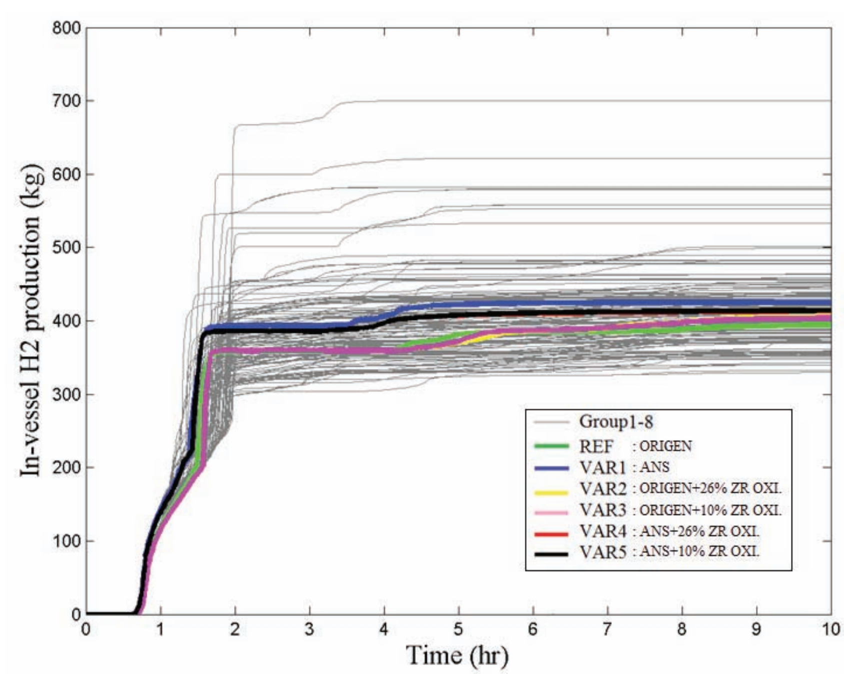


*Figure 6: In-vessel hydrogen production.*

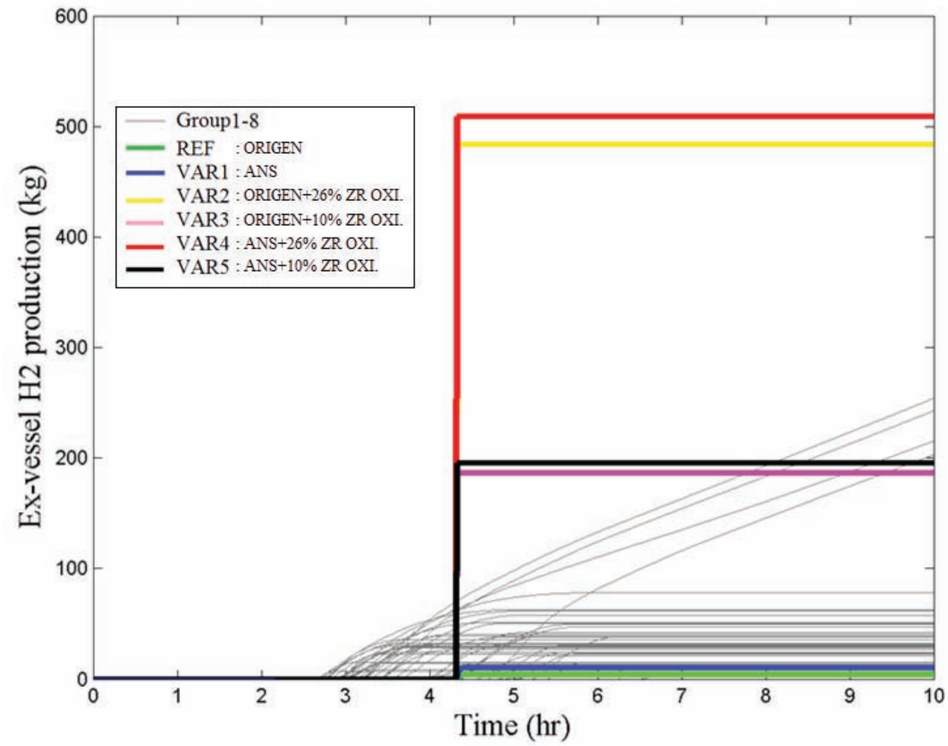


*Figure 7: Ex-vessel hydrogen.*

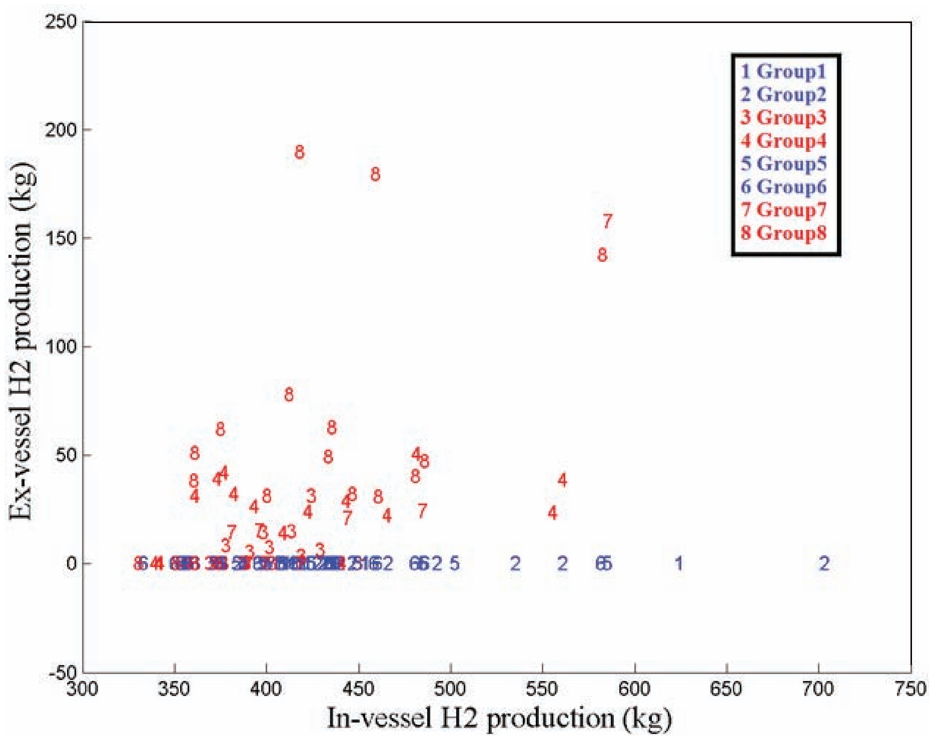


*Figure 8: In-vessel and Ex-vessel hydrogen production at 8 hr.*

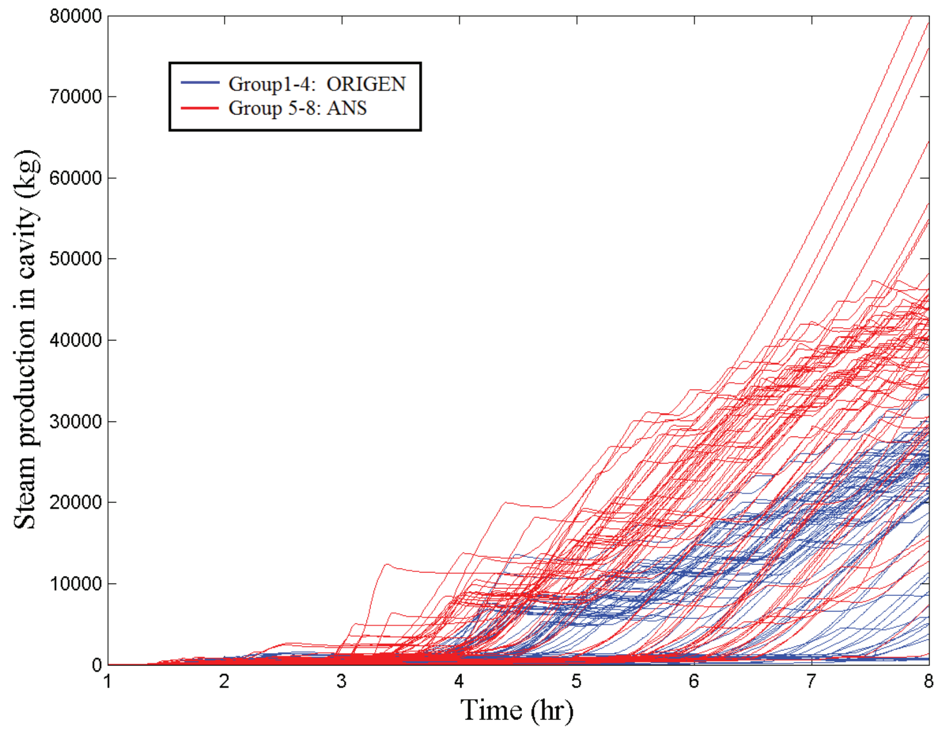


*Figure 9: The steam production in the cavity.*

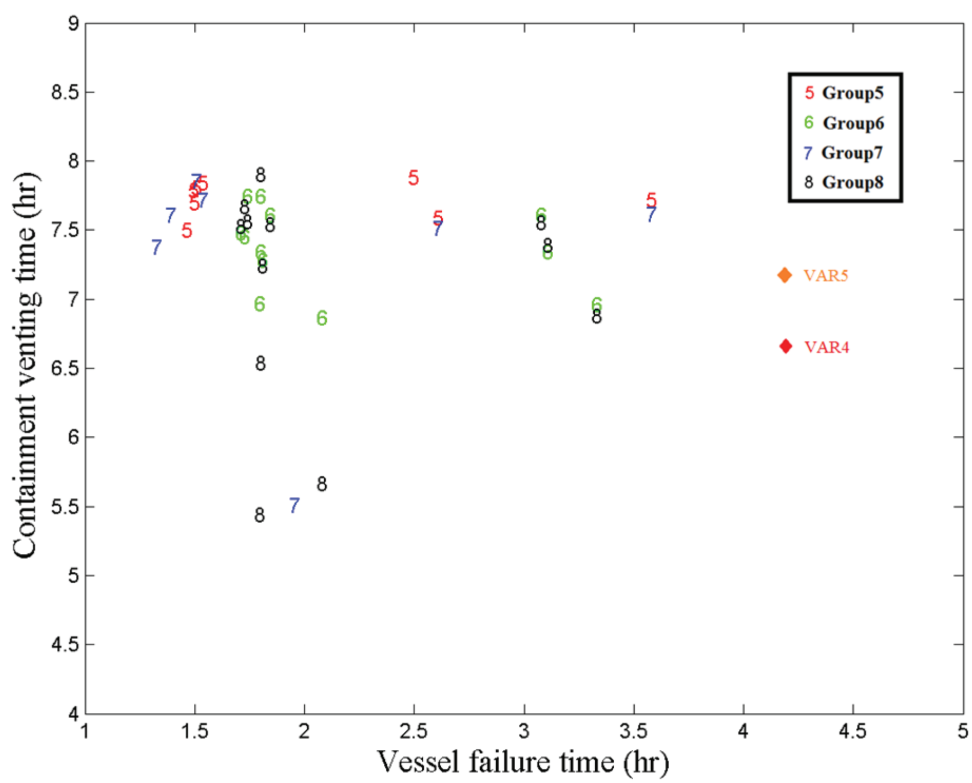


*Figure 10: The containment venting time vs. the vessel failure time.*

## 5. CONCLUSIONS

This paper is concerned with MELCOR assessment of an early containment venting risk of a Nordic BWR plant during the SBO accident scenario. Based on the results of the extensive simulations and sensitivity study, following conclusions can be drawn:

- The calculation of the reference case which reflected the MELCOR Best Practices [2] showed that the early containment venting did not occur in the SBO accident scenario.
- The sensitivity study indicated that the decay heat played a key role in the buildup of containment pressure. The containment venting was not activated if using the ORIGEN decay heat correlation, but might occur in some cases of using the ANS decay heat correlation. Since the decay heat power depends on the plant operation time and refuel scheme, its uncertainty should be considered.
- It was found that the hydrogen produced in the ex-vessel FCI largely accelerated the containment pressurization process, which was not in the modeling capacity of MELCOR2.1 code. Since BWR plants have a larger amount of zirconium in the core region and a smaller containment volume than PWR plants, the oxidation phenomena of metallic component during the FCI should be considered especially for the BWR venting problem. However there is a large uncertainty in the ex-vessel FCI oxidation, more research work should be carried out.

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