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Development of Core Relocation Surrogate Model for Prediction of Debris Properties in Lower Plenum of a Nordic BWR

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ABSTRACT
Severe accident management (SAM) in Nordic Boiling Water Reactors (BWR) employs ex-vessel core debris coolability. Core melt is poured into a deep pool of water and is expected to fragment, quench, and form a coolable debris bed. Success of the strategy is contingent upon the melt release mode from the vessel, which determine conditions for (i) the debris bed coolability, (ii) steam explosion that present credible threats to containment integrity. The characteristics of melt release are determined by the in-vessel accident scenarios and phenomena subject to aleatory and epistemic uncertainties respectively. A consistent treatment of these uncertainties requires Integrated Deterministic Probabilistic Safety Analysis (IDPSA). We employ the concepts and approaches described in Risk Oriented Accident Analysis Methodology (ROAAM) for development of a probabilistic framework (ROAAM+) that is based on extensive uncertainty and sensitivity analysis in risk quantification. Direct application of such fine-resolution models for extensive sensitivity and uncertainty analysis is often unaffordable. We use “surrogate models” (SMs) that provide computationally efficient approximations for the FMs. In this work we demonstrate an approach to the development of Core relocation SM based on the MELCOR code as the full model (FM). We discuss the development of the database of the FM solutions, data mining and post-processing of the results for SM development. Extensive sensitivity and uncertainty analysis is carried out using the FM and implications of the analysis are discussed in detail. We demonstrate how the connection between different stages of severe accident progression is made in ROAAM+ framework for Nordic BWRs.

KEYWORDS
SEVERE ACCIDENT NORDIC BWR ROAAM

1. INTRODUCTION
Severe accidents in nuclear power plants involve a large range of complex interacting phenomena that are normally divided into in-vessel and ex-vessel phases. Thermal hydraulic behavior in the reactor pressure vessel (RPV) and primary circuit, degradation of the core material and its relocation to the lower plenum, formation of in-vessel debris bed, debris bed remelting and melt pool formation in the lower plenum that inflicts thermal load on the lower head, vessel wall and internal structures (such as instrumentation guide tubes (IGTs), control rod guide tubes (CRGTs)) and eventual vessel failure are the phenomena that correspond to in-vessel phase of severe accident progression and define initial conditions for melt release and ex-vessel accident progression (see Figure 1).

Severe accident management in Nordic Boiling Water Reactors (BWR) relies on ex-vessel core debris coolability. In case of core melt and vessel failure, melt is poured into a deep pool of water located under the reactor (lower dry well (LDW)). The melt is expected to fragment, quench, and form a debris bed, coolable by natural circulation of water.
Success of the strategy is contingent upon melt release conditions from the vessel which determine:
(i) properties of the debris bed and thus if the bed is coolable or not.
(ii) potential for energetic interaction (steam explosion) between hot liquid melt and volatile coolant.
Vessel failure mode and melt release conditions are driven by the spatial distribution and the properties of the debris in lower plenum, which provided as initial conditions by core relocation framework in Risk Oriented Accident Analysis Methodology (ROAAM) framework for Nordic BWR (see Figure 2,[1]).

The properties of relocated debris in lower plenum and its spatial distribution are highly influenced by the accident progression scenario and timing of operator actions including possible recovery actions, such as depressurization history, timing and capacity of water injection.

The role of core relocation framework in ROAAM [1] is to predict the effect of severe accident scenario and operator actions on the process of core degradation and relocation and ultimately the spatial configuration and properties of debris bed in the lower plenum for the melt-vessel interaction and vessel failure mode analyses, which are the initial conditions for in-vessel debris coolability [2-4], corium-structure interactions, vessel failure and melt release analyses [5-7].

The goal of this work is to demonstrate an approach to the development and application of Core relocation SM based on the MELCOR code [8,9] as the full model (FM). In particular, we discuss the development of the database of the FM solutions, including FM sensitivity and uncertainty analysis, data mining and post-processing of the results for Core Relocation SM development. Extensive sensitivity and uncertainty analysis is carried out using the FM and implications of the analysis are discussed in detail. We also demonstrate how the connection between different stages of severe accident progression is made in ROAAM+ framework for Nordic BWRs.

2. APPROACH

ROAAM+ framework represents a set of coupled modular frameworks that connects initial plant
damage states (PDSs) to respective containment failure modes (see Figure 2) [1]. In the analysis presented in this paper we consider station blackout (SBO) scenario with a delayed power recovery. We consider a simultaneous loss of the offsite power (LOOP) and backup diesel generators. This results in the simultaneous loss of all water injection systems, including crud purge flow through the control rod drive tubes. This kind of accident is one of the most challenging accidents scenarios for BWR’s as illustrated at Fukushima-Daiichi accident [10] and is among the major contributors to the core damage frequency (CDF) for Nordic BWR according to PSA Level 1 analysis. We consider that the power (external grid or diesel generators) can be recovered after some time delay and emergency core cooling system (ECCS) system can be restarted. According to the considered scenario, the operator can delay activation of the depressurization system to keep coolant in the vessel. Yet, for injection of water with low pressure ECCS, depressurization has to be activated.

The general approach for the development of Core Relocation SM is illustrated in Figure 3. Initial conditions for the analysis of core degradation and relocation to LP are provided from PSA L1 analysis (PDSs with respective frequencies), together with possible recovery and operator actions (Timing). Full Model (FM) is used to generate the data base of full model solutions, as well as to obtain better understanding of basic phenomena and underlying physics.

Post-processing of the results is performed in order to identify i) possible relocation patterns and the influence of severe accident scenario (including timing of possible recovery actions) on the resultant properties of relocated debris in LP [11]; ii) to establish loose coupling between Core relocation and Vessel Failure analyses [5-7,11]. Simplified modelling and data mining techniques are employed in order to develop a surrogate model. Surrogate model is an approximation of the full model (FM), SM is necessary to make extensive uncertainty analysis (aleatory & epistemic) [12] computationally feasible (for instance average MELCOR run time for selected PDSs is ~24-100h, Core relocation SM run time is less than 1sec).

2.1. Full Model and Development of the Data Base of Full Model Solutions

MELCOR input model for Nordic BWR was originally developed for accidents analysis in the power uprated plants [13]. Current MELCOR 1.8.6 (rev2911) input decks have total thermal power output of 3900 MW. The core consists of 700 fuel assemblies of SVEA-96 Optima2 type – which is divided into five non-uniform radial rings and eight axial levels. The primary coolant system is represented by 27 control volumes (CV), connected with 45 flow paths (FL) and 73 heat structures (HS). The vessel is represented by a 6-ring, 14-axial level control volume geometry.

Initial data base of solutions [11] has been generated using uniform sampling to explore the space of
scenario parameters, namely (i) activation time delay of the depressurization of the Reactor Pressure Vessel (ADS) from 1000 to 10000 seconds from the initiating event; (ii) activation time delay of the low-pressure coolant injection (ECCS (LPCI)) from 1000 to 10000 seconds from the initiating event; (iii) maximum mass flowrate delivered by ECCS (with 4,3,2,1 injection trains). The vessel breach condition was not implemented in the analysis.

The sampling MELCOR code execution and data extraction processes are driven by a simulation driver, implemented in MATLAB, which performs: i) Sampling generation. (uniform sampling, DAKOTA interface to generate sampling for sensitivity and uncertainty analysis [14]); ii) MELCOR Input file generation; iii) Execution of the MELCOR code on distributed computing network, which allows performing up to 60 simultaneous threads of calculations. iv) Adaptive refinement of the maximum time step and restarting in case of crashed calculations. v) Extraction of the data to the database of solutions and post-processing of the results.

2.2. Full Model Sensitivity Analysis

Sensitivity analysis using Morris method [20] has been performed for a couple of representative cases from the groups A and B, that represent typical behavior for scenarios with early and late depressurization and late water injection. Morris method is a method for global sensitivity analysis. The guiding philosophy of the Morris method [20] is to determine which factors may be considered to have effect, on model outputs, which can be considered as either negligible, linear or non-linear with other factors. The experimental plan proposed by Morris is composed of individually randomized “one-factor-at-a-time” experiments; the impact of changing one factor at a time is evaluated in turn [21] (see references [20,21] for more details).

For the analysis we selected 5 parameters that can affect the properties of relocated debris in LP. The list with names and correspondent ranges of the parameters selected for MELCOR sensitivity study is presented in the Table 1. Total debris mass, hydrogen mass in containment, metallic fractions in the first and second axial levels and time of onset of massive relocation to LP were taken as response functions in this analysis.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Range</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Time Step (MTS)</td>
<td>[0.001-2.0]</td>
<td>sec</td>
</tr>
<tr>
<td>Particulate Debris Porosity (PDPor)</td>
<td>[0.3-0.5]</td>
<td>-</td>
</tr>
<tr>
<td>Velocity of falling debris (VFALL)</td>
<td>[0.01-1.0]</td>
<td>m/s</td>
</tr>
<tr>
<td>LP Particulate debris equivalent diameter (DHYPDLP)</td>
<td>[0.002-0.005]</td>
<td>m</td>
</tr>
<tr>
<td>Oxidized fuel rod collapse temperature (TRDFAI)</td>
<td>[2500-2650]</td>
<td>K</td>
</tr>
</tbody>
</table>

- Maximum time step (MTS) – specified in executive (EXEC) package, MELCOR calculates its system time step based on directives from the packages, but it cannot take time steps greater than the maximum time and smaller than the minimum time step specified in EXEC package. It has been previously shown in [22,23], that the MELCOR time step has quite significant effect on the results and lack of time step convergence of the solution with reduction of maximum time step. For the analysis we selected the range [0.001-2.0]sec, however this time step can be reduced by the simulation driver in case of crashed calculations.
- Particulate debris porosity (PDPor) – Porosity of particulate debris for all cells in specified axial level.
- Lower Plenum Particulate debris equivalent diameter (DHYPDLP) - MELCOR idealizes particulate debris beds as fixed-diameter particulate spheres.
  - The extent of debris coolability depends among others on the space between the particles. The porosity of randomly packed spheres is found to be approximately 40 % independent of particle size both by experiments and sophisticated computational methods [16]. The range of entrained particle size is considered to be 1-5 mm based on TMI-2 data [15].
  - Based on [18,19] – the following ranges for porosity of particulate debris [0.3-0.5] and LP particulate debris equivalent diameter [0.002-0.005]m were selected.
- Velocity of falling debris (VFALL) - the debris is assumed to fall with a user-specified velocity. This
allows the debris to lose heat to surrounding water in the lower plenum as it falls to the lower head, following failure of the core support plate in each radial ring [17]. Based on [18] and [8,9] the following range for this parameter has been selected – [0.01-1.0](m/s).

- Oxidized fuel rod collapse temperature (TRDFAI) - The temperature at which intact fuel rods are assumed to transition from rod-like geometry to a rubble form can affect the core degradation progression. MELCOR 1.86 default value is 2500K [8,9], which represents the combined effects of eutectic interactions and fractured nature of irradiated fuel pellets. In MELCOR Best Practices as Applied in the State-of-the-Art Reactor Consequence Analyses (SOARCA) Project [18] it is suggested to use a new model for time to fuel rod collapse versus cladding oxide temperature, which range from 2500K(time to failure 1 hour) to 2600K(5 min). Within the scope of this work, the following range was used [2500-2650K].

2.3. Data Mining and Simplified Modelling

An approach for coupling between core relocation and vessel failure analyses is presented in [11]. The approach is based on pattern analysis and clustering analysis. In this approach typical core relocation transients are identified and grouped into patterns [11]. The effect of timing of scenario events (e.g. ADS, ECCS activation time) on the properties of relocated debris is established using clustering analysis (see results in Figure 5 and [11]). Based on the results of pattern and clustering analyses the surrogate model for prediction of the properties of relocated debris and LDW pool conditions has been developed. The surrogate model is of a “look-up table” type (see Figure 4), where major scenario domains have been identified, and the effect of the modelling options in MELCOR has been evaluated. The output of the surrogate model is presented as mean and standard deviation of correspondent distributions of the parameters of interest.

Fig 4. Structure of Core relocation SM.

3. RESULTS

3.1. Properties of Relocated Debris in LP

The analysis of the effect of severe accident scenario and possible recovery actions [11] showed that i) the whole scenario domain can be represented by a limited amount of relocation patterns; ii) the most common relocation pattern is a very rapid relocation to LP; iii) the major part of core materials is relocated to LP shortly after initial core support plate failure (within ~30-60mins); iv) delay in activation of ADS can significantly delay massive core relocation to LP, however it results in greater extent of core oxidation; ECCS is effective in preventing massive core relocation only within relatively small time window after activation of ADS; iv) debris composition (i.e. metallic/oxidic debris fraction) in different layers are highly influenced by severe accident scenario and can be largely classified in limited amount of groups (see Figure 5) (Group A – significant metallic fraction – corresponds to early ADS activation, Group B – Significant oxide fraction – corresponds to late ADS activation, Group C – corresponds to the group of scenarios with relocated debris mass within the range of 100 tons.) The oxide fraction of
relocated debris in LP in both groups A and B is highly correlated with the hydrogen generated during the course of accident (see Figure 5).

From the point of view of vessel failure analysis in ROAAM+ framework, the whole scenario domain can be split into 4 groups:

- Small relocation domain, characterized by small, mostly metallic debris mass (<20 tons).
- Transition domain, characterized by significant range of total debris mass (can range from ~10 to ~200 tons, due to modelling options in MELCOR (e.g. oxidized fuel rod collapse temperature).
- Large relocation domain with small debris oxidation, characterized by large debris mass (over 100 tons) and relatively high metallic debris fraction – which is typical for scenarios with early ADS activation.
- Large relocation domain with significant debris oxidation, characterized by large debris mass (over 100 tons) and relatively small metallic debris fraction – which is typical for scenarios with late ADS activation.

Full model sensitivity analysis has been performed for a couple of representative scenarios for large relocation domain with a) small metallic debris fraction (Case B (ADS Time – 8000sec, ECCS Time – 8500sec) – 246 cases have been simulated) b) high metallic debris fraction (Case A (ADS Time – 2500sec, ECCS Time - 8500 sec) – 246 cases have been simulated) (see Figures 6, 7, 8 and 9 – Pearson and Spearman correlation coefficients, scaled Morris $\mu - \bar{\mu}$ and Morris $\sigma - \bar{\sigma}_i = \sigma_i/\mu_i$ [21], and descriptive statistics in Table 2).

<table>
<thead>
<tr>
<th>Table 2. Descriptive statistics for the Case A and B.</th>
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<tbody>
<tr>
<td>Mean value $\mu$</td>
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<tr>
<td>---------------------</td>
</tr>
<tr>
<td><strong>Debris mass (kg)</strong></td>
</tr>
<tr>
<td>212930</td>
</tr>
<tr>
<td>155940</td>
</tr>
<tr>
<td><strong>Hydrogen mass (kg)</strong></td>
</tr>
<tr>
<td>501</td>
</tr>
<tr>
<td><strong>$T_{ref}$ (sec)</strong></td>
</tr>
<tr>
<td>4510</td>
</tr>
<tr>
<td><strong>Metallic debris fraction in 1st axial lvl.</strong></td>
</tr>
<tr>
<td>0.25-0.79</td>
</tr>
<tr>
<td><strong>Metallic debris fraction in 2nd axial lvl.</strong></td>
</tr>
<tr>
<td>0.19-0.45</td>
</tr>
<tr>
<td><strong>LDW Pool Temperature (K)</strong></td>
</tr>
<tr>
<td>326.1-328.1</td>
</tr>
<tr>
<td><strong>Containment Pressure (Bar)</strong></td>
</tr>
<tr>
<td>2.21-3.08</td>
</tr>
<tr>
<td><strong>LDW Pool Depth (m)</strong></td>
</tr>
<tr>
<td>6.59-8.0</td>
</tr>
</tbody>
</table>
Figure 6 shows the sensitivity indices of the amount of relocated debris in LP to the modelling parameters in MELCOR. The results indicate that for the Case B, LP debris mass is largely influenced by TRDFAI, where larger values of TRDFAI will yield smaller debris mass (e.g. for TRDFAI = 2650K MELCOR predicts approximately 18 tons of debris in LP, while for TRDFAI = 2500K debris mass can reach 215 tons). Also, judging by Morris $\bar{\sigma}$ and correlation coefficients, there is a linear dependency between TRDFAI and the resultant mass. Debris mass in LP predicted by MELCOR for the Case B ranges from 18 to 215 tons with mean value – 135 tons and standard deviation – 36.5 tons. For the Case A, debris mass in LP is in the range from 155 to 264 tons, with mean value – 212.9 tons and standard deviation – 20 tons. In case A, according to Morris method sensitivity analysis results, the most influencing parameters are particulate debris porosity (PDPor), falling debris velocity (VFALL) and oxidized fuel rod collapse temperature (TRDFAI), and, judging by $\bar{\sigma}$ values, all involved in non-linear interaction with other parameters.

![Fig 6. Sensitivity of debris mass in LP to modelling parameters in MELCOR.](image1)

Figure 7 shows the sensitivity indices of the time of massive relocation to LP ($T_{ref}$). For the Case B $T_{ref}$ is largely influenced by particulate debris porosity (PDPor) and oxidized fuel rod collapse temperature (TRDFAI), as well as debris falling velocity (VFALL) – larger values of TRDFAI yield later fuel failure time, thus, delaying massive relocation to LP. It ranges from 0 sec (i.e. no core support plate failure) to 31000 sec with mean value of ~7500 sec and standard deviation of ~2600 sec. For the Case A, $T_{ref}$ lies within relatively small time window from 4510 to 5870 sec with mean value of 5251 sec and standard deviation 234 sec. The most contributing factors are PDPor, TRDFAI and VFALL.
However, the effect of these parameters on the uncertainty in $T_{ref}$ is insignificant.

Figure 8 shows the sensitivity indices of the amount of hydrogen produced during the accident to the modelling parameters in MELCOR. In Case B it ranges from 969kg to 1649kg, with mean value of 1148kg and standard deviation 126kg. The most important factors for hydrogen production are particulate debris porosity (PDPor) and debris falling velocity (VFALL). For the Case A, the hydrogen mass ranges from 501 to 1545kg with mean value of 851kg and standard deviation 218kg. The most important factors for hydrogen production in Case A are PDPor, TRDFAI and MTS. The results indicate that there is non-linear interaction between the parameters used in this study.

![Figure 8. Sensitivity of hydrogen mass to modelling parameters in MELCOR.](image_url)

Figure 9 shows sensitivity indices of the metallic debris fraction in the first axial level to the modelling parameters in MELCOR. Metallic debris fraction in the 1st axial level ranges from 0.13-0.97 with mean value 0.35 and standard deviation 0.12 (scenarios with 0.97 metallic debris fraction corresponds to the cases where MELCOR does not predict core support plate failure and massive relocation to LP), and from 0.26 to 0.79 with mean value 0.48 and standard deviation 0.13 – for the Case B and A correspondingly. The most important factors for metallic debris fraction in the first axial level are VFALL for the Case A and VFALL, PDPor, DHYPDLP for the Case B.

![Figure 9. Sensitivity of metallic debris fraction in the 1st axial level to modelling parameters in MELCOR.](image_url)

The results of sensitivity study can be summarized as follows:
- TRDFAI (oxidized fuel rod collapse temperature) – the temperature at which a transition from intact fuel rod geometry to a rubble form is assumed. There is quite significant influence of TRDFAI on the
total amount of relocated debris (see Figure 6). This influence can be explained by the time (and respective generated heat) that is necessary to reach the fuel failure condition. With increase of TRDFAI it takes more time to heat up the fuel assemblies to the point at which they fail, convert into particulate debris, accumulate and cause support plate failure at certain time \( T_{\text{ref}} \) (as illustrated by the values of the correlations in Figures 6 and 7). The difference in relative importance of TRDFAI between Cases A and B (low and high pressure respectively) can be explained by different core heat up rates in these scenarios. The core heat up rate in Case A is higher (because there is no water in the core region) compared to Case B, therefore significance of TRDFAI is lower in Case A compared to Case B. TRDFAI has significant effect on the hydrogen production in Case A and B, where higher values of TRDFAI can result in longer periods of time during which the intact core structures are exposed to oxidation. However, the overall effect on the mass of hydrogen produced (see values of the correlation coefficients in Figure 8) is non-monotonic.

- PDPor (particulate debris porosity) – is defined for all cells in specified axial level. When structure failure criteria are reached the structures in the cell are converted into porous debris with the user defined porosity. Particulate debris in MELCOR are represented as spheres with an equivalent diameter. When debris relocates and joins a particulate debris bed in a computational cell, it is assumed that the volume of particulate debris increases and node porosity decreases [9]. According to [8], the flow through the core node with particulate debris decreases along with the porosity, however MELCOR never completely blocks the flow. Reduced flow affects both, heat removal from the core and particulate debris by escaping steam, and core/debris oxidation rate (Figures 6, 7 and 8). Figure 6 indicates that PDPor has an important non-linear effect on LP debris bed formation, it might be due to: (i) steam flow through the core nodes with increased porosity increase oxidation (see Figure 8); (ii) additional steam generation in LP and cooling of outermost rings upon core support plate failure. The difference between Cases A and B can be explained by the effect of depressurization. In Case A, the water level after depressurization drops below the active core region, the uncovered core starts to heat up, eventually reaching the point where control rods/blades, canisters undergo degradation and relocate downwards to the core plate, where its either rest on top as PD, or refreezes as conglomerate, or flows through the openings into the lower plenum. The variation in PDPor, as a result will affect both, cooling of the core by escaping steam (see Figures 6, 7) and core oxidation (see Figure 8). In Case B, the water level in core decreases gradually, so the relative importance of this parameter on steam flow rate through the core is lower, compared to the Case A, which can be observed in (Figures 6, 7 and 8). When it comes to core support plate failure (see Figure 7), it seems that larger PDPor values promote core cooling by escaping steam, but, on the other hand, enhance core oxidation and chemical heat production (especially for the Case A, where oxidation starts after water level dropped below active core bottom, so the results in Case A are more sensitive to PDPor compared to the Case B), that may result in earlier degradation of the fuel assemblies and earlier failure of core support plate \( T_{\text{ref}} \), the extent of the effect of this parameter on core cooling/oxidation in different scenarios is also reflected in correlation coefficients in Figure 7. The effect of PDPor on the metallic debris fraction (see Figure 9) can be explained by the extent of core oxidation, since there is a clear distinction between Case A and Case B, which is quite evident in Table 2.

- DHYPD (Lower plenum particulate debris equivalent diameter) – MELCOR uses this parameter to calculate heat transfer surface area of the debris in LP, note that MELCOR equates the oxidation surface area to the heat transfer surface area of the node; so it should have an effect on the debris oxidation and steam generation rate. However, based on the results of sensitivity study the effect of this parameter within considered ranges on debris mass, hydrogen mass, time of core support plate failure was found to be smaller compared to the effect of the other parameters (Figure 6, 7 and 8). On the other hand, it might be involved in interaction with other parameters (e.g. PDPor and VFALL). Further analysis is necessary to determine the effect of particulate debris diameter and heat transfer coefficients in in-vessel debris quench model in MELCOR on the results. The effect of DHYPD on the metallic debris fraction in 1st axial level (Figure 9) is yet to be explained.
- VFALL (velocity of falling debris) - MELCOR does not have a mechanistic model for debris dropping into the lower plenum. Instead a number user-specified parameters control the rate at which material relocates into the lower plenum and the effective heat transfer from and associated oxidation of the debris slumping into lower plenum water [24]. The effect of VFALL on the amount of the debris in LP (see Figure 6) can be explained by steam generation during core slumping that can affect both: steam cooling of core/core debris and enhanced oxidation. However, based on the results, it seems that the core slumping, together with its modelling parameters (such as VFALL, DHYPDLP and others [8]) has different effect in different severe accident scenarios, e.g. in Case A the core heat up rate in the 1st, 2nd and 3rd radial rings is significantly higher compared to the periphery of the core (rings 4 and 5; ring 5 can also radiate a fraction of its decay heat to the shroud) – see Figure 10a, while in Case B, due to gradual coolant evaporation, the core heats up more evenly in all radial rings – see Figure 10b. Prior to core plate failure ($T_{ref}$) there is quite significant difference in fuel temperature in the 4th and 5th radial rings between Cases A and B (see Figures 10c, 10d). The slumping of the core debris to lower plenum generates steam flow through the core, including outer rings, where it can i) provide steam cooling; ii) cause enhanced oxidation and chemical heat production, if the cladding temperature in the nodes exceeds oxidation cut-off threshold ~ 1100K. Further analysis of the effect of VFALL, PDPor, DHYPDLP on the flow and hydrogen generation in different radial rings and properties of relocated debris is necessary.

Fig 10. Core fuel temperature map prior to: onset of fuel rods failure for a) Case A; b) Case B; core debris slumping to lower plenum (at $T_{ref}$) for c) Case A; d) Case B.\(^1\)

\(^1\) TRDFAI equals to 2500K in these figures.
- MTS (Maximum time step) – based on the results of sensitivity study, MELCOR maximum time step has a very little impact on the mass of relocated debris and the time of core support plate failure, on the other hand, it has some non-negligible effect on the extent of core oxidation, which is linked to the amount of hydrogen produced (see Figure 8) and the metallic debris fraction (see Figure 9) – which can be caused by the complex non-linear interactions between physical models in MELCOR and their sensitivity to the time step.

4. CONCLUSIONS

In this study we present a method for the development of computationally efficient core relocation surrogate model which can be used in ROAAM+ framework. ROAAM+ framework for assessment of the effectiveness of Nordic BWRs SAM strategy employs loosely coupled models for modeling of the multistage severe accident progression scenarios and respective phenomenology. Core relocation framework is one of the important elements, which provides initial conditions for the later stages of the accident progression.

The approach for the development of core relocation framework includes: i) generation of the data base of full model solutions, in this work we use MELCOR code as a full model for assessment of the properties of relocated debris in LP of Nordic BWR; ii) post-processing of full model solutions to identify possible domains of scenarios that lead to similar debris properties in lower plenum; iii) full model sensitivity and uncertainty analysis to identify the most influential parameters and quantify the uncertainty in prediction of the properties of relocated debris; iv) development of core relocation SM.

We found that the whole scenario domain can be split into four groups, namely: small relocation domain; transition domain; large relocation domain with significant debris oxidation; large relocation domain with small debris oxidation.

Sensitivity analysis results for large relocation domain show that the most influential parameters for determining debris mass in LP and time of core support plate failure are: oxidized fuel rod collapse temperature and particulate debris porosity. Non-linear interactions between the effects of different parameters might have an effect on the results. Hydrogen generation and metallic debris fraction in the first axial level are mostly affected by: velocity of falling debris and particulate debris porosity. Variation of the maximum time step result in noticeable variations in the code response. This indicates that complex non-linear interactions between physical models in MELCOR might lead to difficulties with achieving numerical convergence and respective variations in code predictions. In order to overcome this issue, it was proposed to characterize the distribution of the properties of relocated debris.

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