Comparison of MELCOR and MAAP calculations of core relocation phenomena in Nordic BWR’s

Master of Science Thesis by:

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ABSTRACT

Since the crisis in Fukushima, severe accident progression during a station blackout (SBO) accident is recognized as a very important area for accident management and emergency planning. Therefore, a better understanding of the phenomenology and progression of core melt behavior is needed in order to develop mitigation strategies. The major objective of this Master’s thesis was to perform a comparison between MELCOR (version 1.8.6) and MAAP (version 4.0.6) calculations to investigate possible reasons for differences in prediction of the core degradation and in-vessel relocation phenomena in Nordic BWR’s. By addressing uncertainties in modeling between the codes, an increased understanding of the differences in the underlying models used for prediction of degradation and debris relocation was gained. Parameter studies were performed in MELCOR to address uncertainties associated with the modeling of the phenomenological processes involved in the melt progression. In order to plan the analysis, hypotheses were stated and evaluated. A long-term SBO with all power lost, except battery capacity to operate the safety relief valves (SRV’s) and the automatic depressurization system (ADS) was simulated, which is the main contributor to the core damage frequency.

Several major discrepancies in input parameters e.g. the amount of initial UO$_2$ mass, irradiation time and debris particle size were identified, which had not been taken into consideration in previously performed comparisons. The MELCOR Nordic BWR model (ASEA-Atom BWR 75) was updated in accordance to available MAAP data and the uncertainty arisen from discrepancies in input was successfully reduced. However, no alteration in nodalization was performed.

The comparison indicates major differences in debris mass relocation progression (predicted to take 1.8 times longer in MELCOR), failure modeling and oxidation modeling. A significant difference in the representation of debris characteristics and transition in lower plenum were also identified. Moreover, MAAP predicts 9-10% higher level of decay heat than MELCOR, a deviation which remained unsolved. However, decay heat is an important factor but it cannot alone explain the remaining differences in prediction of the relocation progression. Furthermore, the maximum time step was identified as the major contributor to uncertainties in MELCOR results, which significantly affects the outcome during the late phase of the core degradation progression.

Through the study increased knowledge about in-vessel core degradation and relocation phenomena, timing of key events and resulting properties of the debris bed in the vessel lower plenum of Nordic BWR’s was gained. However, due to several unresolved issues regarding failure modeling, oxidation modeling and decay heat calculation, further comparisons are necessary in order to fully understand the differences in severe accident modeling between MELCOR and MAAP.

The study was carried out at Lloyd’s Register Consulting - Energy AB (LRC) in collaboration with the Nuclear Power Safety department at the Royal Institute of Technology (NPS-KTH).
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<th>Description</th>
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<tbody>
<tr>
<td>ADS</td>
<td>Automatic Depressurization System</td>
</tr>
<tr>
<td>AFW</td>
<td>Auxiliary Feed Water</td>
</tr>
<tr>
<td>BWR</td>
<td>Boiling Water Reactor</td>
</tr>
<tr>
<td>CRGT</td>
<td>Control Rod Guide Tube</td>
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<tr>
<td>CVS</td>
<td>Containment Venting System</td>
</tr>
<tr>
<td>DC</td>
<td>Down comer</td>
</tr>
<tr>
<td>DW</td>
<td>Drywell (LDW+UDW)</td>
</tr>
<tr>
<td>ECCS</td>
<td>Emergency Core Cooling System</td>
</tr>
<tr>
<td>EPRI</td>
<td>Electric Power Research Institute</td>
</tr>
<tr>
<td>IDCOR</td>
<td>Industry Degraded Core Rulemaking Program</td>
</tr>
<tr>
<td>KTH</td>
<td>Kungliga Tekniska Högskolan</td>
</tr>
<tr>
<td>LDW</td>
<td>Lower Drywell</td>
</tr>
<tr>
<td>LPCI</td>
<td>Low Pressure Coolant Injection</td>
</tr>
<tr>
<td>MAAP</td>
<td>Modular Accident Analysis Program</td>
</tr>
<tr>
<td>MCCI</td>
<td>Molten Core Concrete Interaction</td>
</tr>
<tr>
<td>MVSS</td>
<td>Multi Venturi Scrubbing System</td>
</tr>
<tr>
<td>NPS</td>
<td>Nuclear Power Safety Division</td>
</tr>
<tr>
<td>PSA</td>
<td>Probabilistic Safety Analysis</td>
</tr>
<tr>
<td>PWR</td>
<td>Pressurized Water Reactor</td>
</tr>
<tr>
<td>RHR</td>
<td>Residual Heat Removal</td>
</tr>
<tr>
<td>RPV</td>
<td>Reactor Pressure Vessel</td>
</tr>
<tr>
<td>SAM</td>
<td>Severe Accident Management</td>
</tr>
<tr>
<td>SBO</td>
<td>Station Black Out</td>
</tr>
<tr>
<td>SNL</td>
<td>Sandia National Laboratories</td>
</tr>
<tr>
<td>SRV</td>
<td>Safety Relief Valve</td>
</tr>
<tr>
<td>SSM</td>
<td>Strålsäkerhetsmyndigheten</td>
</tr>
<tr>
<td>TOAF</td>
<td>Top of Active Fuel</td>
</tr>
<tr>
<td>UDW</td>
<td>Upper Drywell</td>
</tr>
<tr>
<td>U.S. NRC</td>
<td>U.S Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>WW</td>
<td>Wetwell</td>
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1 Introduction

1.1 Motivation

Since the crisis in Fukushima in 2011, severe accident progression during a SBO accident is recognized as a very important area for accident management and emergency planning [1]. A better understanding of the phenomenology and progression of core melt behavior is needed in order to develop mitigation strategies and to evaluate possible consequences to ensure minimum release of radionuclides. Fortunately, severe nuclear accidents rarely occur but this subsequently limits the understanding of the complex phenomena involved. Epistemic uncertainties i.e. lack of state-of-knowledge are the major source to uncertainty in PSA level 2 results [2]. Through investigations of TMI-2, Chernobyl and Fukushima much knowledge has been gained in the area of core degradation but large uncertainties in several major phenomena still exist, which affects the uncertainty of results predicted by the severe accident analysis codes.

According to Figure 1, the accident progression involves several phenomenological stages, which can lead to containment failure unless coolability is achieved. The multistage path from the initial plant damage state to the containment threats is an important source of complexity and uncertainty. Severe accident management (SAM) in Nordic BWRs relies on ex-vessel core debris coolability [3]. However, conditions created at earlier stages can significantly affect configurations and problem statements at later stages of the accident progression [3]. Hence, the in-vessel core degradation and relocation is an important stage of the severe accident progression. For instance, the early stages determine not only the characteristics of the debris in the vessel lower plenum (mass, composition, thermal properties) it also affects the timing of relocation and decay heat [4]. Furthermore, threats to containment integrity e.g. steam explosion and formation of a non-coolable debris bed are dependent on the melt release and pool state, determined partly in earlier stages of the progression. Hence, gained knowledge about core degradation and the in-vessel processes and phenomena is necessary in order to evaluate the whole progression and later stages i.e. ex-vessel phenomena and estimation of the source term.
Limited comparisons have been performed with the current MELCOR Nordic BWR model and MAAP results. Several unsolved issues discovered in previous comparisons with MAAP [5], [6] imply the necessity to evaluate differences in prediction of the in-vessel melt progression further and to reduce uncertainties in code inputs.

In Sweden today, MAAP is the only official tool used in severe accident analysis and PSA level 2 applications. Due to costly licensing, MAAP usage is generally limited to nuclear utilities and vendors. The MELCOR code on the other hand, is used by regulators and academics and can be provided without cost if agreement is made to Strålsäkerhetsmyndigheten (SSM). Increased MELCOR competence and further development of the current MELCOR model will enable LRC to simulate new assignments independent from MAAP. If this can be achieved, MELCOR may serve as an additional tool for decision-making.

Hence, the main motivation of the present work is to identify and evaluate sources contributing to differences obtained between MAAP and MELCOR in the prediction of the in-vessel accident progression during a SBO by i) reducing discrepancies in the inputs and ii) increasing the understanding of underlying models used for prediction of core degradation and debris relocation.
1.2  Background

Despite years of research on accident progression and core behavior, it is still possible for unexpected events and failure combinations to exceed the reactor design range, most recently seen in Fukushima. The phenomenology of severe accidents is extremely complex and therefore associated with large uncertainties [7], [8]. Increased knowledge about core degradation and the impact of the phenomena and responses taking place during core degradation and the in-vessel relocation process is essential to understand the plant behavior and estimate the source term. Since the accident at TMI-2 in 1979, significant knowledge has been gained and improvements made regarding severe accident progression and safety management. New phenomenology has resulted in increased understanding of core relocation phenomena and the underlying mechanisms. The realization by industry and regulators that severe accidents with substantial core degradation were credible, led to increased research efforts by organizations such as Electrical Power Research Institute (EPRI) and United States Nuclear Regulatory Commission (U.S NRC) to acquire a basic knowledge of the progression and consequences of a wide range of risk-dominant severe accidents [9]. Through the development of computer codes, which are capable to model the plant’s response to different outer circumstances, significant insight into severe accident progression is gained. Computer codes have therefore become the repository of this vast body of knowledge on severe accidents [10].

The MELCOR and MAAP codes are used by many organizations world-wide to calculate the response of commercial nuclear power plants to postulated severe accidents. Unfortunately, the simulation of this type of phenomena is sometimes limited by the lack of knowledge on the phenomena, on the physical parameters entering in the models and on the input data related to the scenarios of the accident [7]. Although both MELCOR and MAAP are designed to address the same general problem (i.e. the transient response of nuclear reactor systems to severe accidents), the codes have been developed independently from each other, originally with different focus on technology (BWR’s respective PWR’s).

1.2.1  Uncertainties in severe accident modeling

Different modeling strategies are generally attributed to either mechanistic or integrated severe accident codes. Mechanistic codes usually attempt and claim to provide detailed, physically based modeling describing deterministically the continuous sequence of processes and events e.g. SCDAP/RELAP5 [11]. In contrast, integrated codes such as MELCOR and MAAP combine phenomenological and parametric models in order to simulate the overall response of the plant during the accident progression. Integrated codes are not designed to perform best-estimate simulations, rather to bound important phenomena [8]. The application range of the parametric models applied within the integrated codes is limited for profound understanding and modeling of phenomena and interpretations should be made with special care [12]. In addition, the necessity to use less detailed models bears the risk of making the results very sensitive to the choice of parameters and judgment of the individual user [11].
Through the development of computer codes, significant insight of severe accident progression is gained even though uncertainties in physical processes and modeling are of great concern. There are several factors contributing to the uncertainty in all severe accident simulations, which are presented below:

i) Modeling uncertainty (incl. representational and scaling uncertainty) [13]
ii) Code input
iii) Numerical uncertainty (e.g. time step)

Modeling uncertainty arises due to uncertainties in the empirical data and conditions of the experiments, which were used to develop the computer code models. In addition, representational uncertainty arises because of uncertainties in the understanding of the physical processes itself due to limited data available. Furthermore, the scaling uncertainty appears when extrapolation is made to conditions or scales beyond those for which the empirical data was obtained [13]. Despite the fact that both MELCOR and MAAP are benchmarked against similar fuel melt experiments e.g. VERCORS and Phébus to provide insights into core melt progression at the level of single fuel assemblies, the tests are not reactor scaled. The extrapolation of the tests in the development of the code models has resulted in divergences when simulating conditions at reactor scale [14], [13]. Besides the inherent uncertainties mentioned above, the numerical uncertainty in the code input also adds uncertainty to the calculations and therefore becomes important in code comparison. If the initial conditions stated in the inputs differ, the prediction of the sequence will differ and subsequently affect the results to some extent. By reducing the uncertainty in code input i.e. make sure similar initial core masses, failure criteria etc. are applied, differences obtained in the results will address uncertainties in modeling between the codes.

1.2.2 Overview of MELCOR

MELCOR [15] is developed by Sandia National Laboratory (SNL) under contract from the U.S Nuclear Regulatory Commission (NRC). It is a fully integrated severe accident code, which enable simulations of the whole accident progression, from the initiating event to the source term, i.e. radioactive release to the surrounding environment. The MELCOR code is capable to model a range of physical phenomena, some of them with certain interest in the current study are:

- Thermal-hydraulic responses
- Core uncovering, fuel heat up, cladding oxidation, fuel degradation and core material melting and relocation
- In-vessel hydrogen production due to oxidation of steel, Zircaloy and Boron (B\textsubscript{4}C)
- Failure of the vessel lower head and transfer to reactor cavity
- Decay heat estimation
Initially, MELCOR code was predominantly parametric with respect to modeling of complicated physical phenomena due to limited knowledge of reactor accident physics. However, phenomenological uncertainties have been reduced and the user demand have increased, model implementations in MELCOR have become best estimate in nature [15] and results have been validated against a large number of experimental tests, both separate effects test and large integral experiments [16]. Current use often includes sensitivity and uncertainty analysis. Therefore many of the mechanistic models have been modeled with optional adjustable parameters i.e. sensitivity coefficients. This enables changes of certain parameters in the physical model that otherwise are hardwired constants and need modification in the Fortran source code. Thus, the effect of particular modeling parameters on the calculated transient is addressed without affecting the mechanistic nature of modeling [15].

MELCOR modeling is flexible and uses a control volume approach, thus the building is subdivided into user-defined control volumes and flow paths connecting the cells. The majority of the input records are not required to enable simulations; instead default values are applied if no other input is made. The default value allows an order-of-magnitude reliability [15]. The MELCOR code comprises a number of packages, each modeling a different portion of the accident phenomenology. For instance, all thermal-hydraulics of the control volumes are treated in the control volume hydrodynamics (CVH) package while the core (COR) package calculates the thermal response of core and lower plenum structures, debris formation, vessel breach, oxidation processes etc. Furthermore the radionuclide (RN) package tracks fission products relocation and the inventory is used by the decay heat (DCH) package to provide decay heat estimation in the reactor. All physical calculations are simulated in parallel by each of the different packages.

The calculations are executed in two steps. The user input, MELGEN, is where the majority of the input and problem definition is stated. The second part is MELCOR, the program itself where the desired length of the simulation and time steps are defined. Simulations produce several output files; a diagnostic (.DIA) file containing input errors and non-fatal, an output file (.OUT) generated separately from both MELGEN and MELCOR, a binary restart file (.RST) comprising all necessary data to restart MELCOR, a plot file (.PTF) and a message file (.MES) containing the occurrence time for significant event such as core support plate failure and melt ejection.

1.2.3 Overview of MAAP

MAAP is a fast-running computer code that provides a flexible tool for evaluating the in-plant effects of a wide range of postulated accidents. It treats the full spectrum of important phenomena that could occur during an accident and is also used for examining the impact of operator actions on accident progressions [17]. Originally, MAAP was developed in the early 1980s by Fauske & Associates LCC (FAI) for the Industry Degraded Core Rulemaking (IDCOR) program and after completion, the ownership of MAAP was transferred to the Electrical Power Research Institute (EPRI) and still is today. Due to an increasing demand for analysis of beyond-design-base events, MAAP applications have greatly increased over the past 30 years [18]. MAAP results have been
successfully benchmarked against major experimental studies related to severe accidents. Thus, MAAP has become the primary tool and is extensively used throughout the world to support PSA level 2 severe accident management strategies and to address emergency issues [18]. During the event at Fukushima and in the support of post-Fukushima activities, MAAP has continued to play a significant role in the understanding of accident progression and mitigation [18].

Due to MAAP’s costly licensing criteria it is mostly used by nuclear utilities and vendors. Furthermore, many aspects of MAAP and belonging documents are not publicity available. Hence, details of the models and calculations applied within the MAAP code are confidential and unavailable in this study. This caused some limitations, which are discussed further in section 2.1.3.

1.3 In-vessel severe accident phenomena

Several scenarios of accidents may lead to what is defined as a severe accident, characterized by core degradation i.e. loss of geometrical integrity by melting or debris formation [7]. As a consequence of insufficient core cooling during a SBO, the decay heat is unsuccessfully removed and as the remaining water boils off, the core becomes uncovered. Initially, core heat up is determined by the axial and radial power profiles of the decay power and the cooling conditions imposed by the residual water level in the core [11]. As a consequence, the core temperature will increase and threaten the structural materials and eventually the fuel, subsequently causing core damage.

Core degradation can be categorized into two different phases, i) the early phase, which covers the start of core uncover, heat up process and melting of reactor materials with relatively low melting points (Zircaloy cladding, B$_4$C absorber material) but with core geometry still kept essentially intact and ii) the late phase that refers to the period where ceramic materials (UO$_2$) are melting, formation of molten pools, relocation to the lower plenum and eventually the vessel failure of the lower head occur [19]. Generally, the early phase of core degradation is dominated by thermal-hydraulic phenomena and sophisticated thermal-hydraulic modeling is important of the reactor response and timing of events henceforth. The late phase is dominated by additional complicated phenomena e.g. oxidation and core material interaction in addition to the thermal-hydraulics. Severe accidents codes are more diversified, less validated and hence have more uncertainties in the late phase [20].
1.3.1 Core degradation and relocation to lower plenum

Relocation is usually initiated by the mechanical failure of the ZrO\textsubscript{2} layer on the cladding, which functions as a protective oxide shell and prevents the molten cladding behind to relocate. For low-pressure accident sequences, cladding starts to balloon and rupture once the core temperature reaches 1000-1200 K [8]. A result of fuel cladding failure is the release of volatile fission product gases, which might result in severe consequences if being released to the environment. The melting control blades and fuel rods relocate downwards to cooler areas and refreezes and form a crust (or conglomerated debris as it is called in MELCOR), a phenomenon denoted candling [11]. Resolidification of liquid material cause flow blockages that reduces the local fluid flow affecting the oxidation processes. Hence, steam starvation zones are created that cannot be oxidized and are likely to produce Zircaloy rich melt that will not be oxidized until relocation to another part of the core [8]. Local blockages also prevent melt from further relocation, which enables the formation of molten pools. The potential for molten metal relocation through the core support plate when it is still intact was identified in the XR2-1 experiment performed at SNL [13]. Some of the molten control rods and canisters will be able to relocate into lower plenum before plugging the core support plate. Eventually, the core support plate, which separates the core region from the lower head, cannot support the load of the accumulated debris on top and it fails followed by the ejection of large amount of debris into the lower head.

1.3.2 Debris characteristics in lower plenum

The debris bed configuration in the lower plenum is associated with large uncertainty due to the complex physical phenomena involved. Thus, the relative amount and locations of phases and layers in the lower head cannot be described in a deterministic way with the current state of knowledge [8]. Some important phenomena involved in the debris configuration are presented in Figure 2.

![Figure 2. Phenomena affecting the lower plenum debris configuration [8]](image)
The consequence of mass relocation to lower plenum depends strongly on the amount of available water. As the hot debris comes in contact with remaining water in the lower head, it will result in coarse fragmentation (particulate debris), which can involve a non-energetic interaction (steam spike) or cause an energetic steam explosion and severely damage the lower head when remaining metals becomes oxidized [21]. As molten material accumulates in the bottom of the lower head, the composition of the quenched debris will vary with height due to different material properties [22].

The key parameter for the particulate bed behavior is the porosity. 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 [23]. The range of entrained particle size is considered to be 1-5 mm based on TMI-2 data [24]. However, the porosity only shows a weak dependence on the variance of the size distribution [23]. If melt enters the lower head in the form of a large, single jet (diameter of ~50 cm) after complete failure of the lower core support, the interaction with the water will be limited. The relocated melt will remain largely liquid and will immediately form a molten pool surrounded by crusts in the lower head, possibly with an overlying water layer on top [11]. The relative timing and nature of relocation process has an important effect in the stratification of the molten materials. Early relocation of ceramic materials results in the formation of multiple layers of ceramic and metallic layer in the lower plenum, whereas a later relocation may promote mixing and reduced the number of layers [8]. Differences in composition and the amount of liquid melt will have an impact on the timing of vessel failure due to different thermal conductivity and also affect the ex-vessel accident progression e.g. steam explosion and coolability [4].

Gap formation between the debris and the lower head wall as inherent cooling mechanism was proposed to explain the integrity and rapid cooling of the lower head during the TMI-2 accident [8], [24]. Microscopic cracks in the wall are supposed to trap water, which evaporates as the debris relocates to the lower plenum producing a contact resistance gap with a thickness typically in the range 1-2 mm [25]. Calculations performed in SCDAP/RELAP5-3D show a significantly reduction in lower head surface temperature achieved by accounting for corium-to-vessel-gap compared to a non-existing gap [25]. The opinion whether or not gap formation is possible goes apart. Despite multiple experiments providing evidence and benefits in core cooling by the existence of a gap, there are still large uncertainties in the possibility of water ingression. Too many intrinsic limitations and requirements regarding e.g. heat flux, water presence and closure of the gap makes it difficult to accept the mechanism as credible in the vast majority of cases at low pressure [8]. The treatment of gap cooling when the debris enters the bottom of the lower head is yet not implemented in MELCOR.
1.3.3 In-vessel hydrogen generation

Hydrogen is generated in the oxidation processes of the core materials i.e. Zircaloy, stainless steel and B$_4$C. Oxidation is important in view of the severe accident progression due to the generation of reaction heat, which accelerates the core heat up. Zircaloy and steam oxidation is considered to be the most important process with respect to hydrogen production and consequences on core degradation [8]. When the temperature increases to a range of 1500-1700 K the exothermic heat from Zircaloy oxidation exceeds the decay heat and the cladding heat up rate increases significantly from about 1 K/s to 10-20 K/s [26]. The production rate of hydrogen depends strongly on the participating masses, temperatures, surface areas and the availability of water and steam [19]. The temperature at which the ZrO$_2$ shell breaks and the underlying molten oxidizing metal is released, is known to be a dominant factor in the hydrogen production [27]. However, a major uncertainty in determining the hydrogen generation is the timing of the cladding failure and loss of core geometry due to the complexity in estimation the amount Zircaloy surface area (the equivalent diameter of particulate debris) and the effect of flow blockages [19], [21]. The oxidation process of B$_4$C is highly exothermic and generates 6-7 times more hydrogen compared to oxidation of the same amount of Zircaloy [28]. However, the amount of B$_4$C is considerably less than the mass of Zircaloy present in the reactor and therefore the contribution is less significant.

As demonstrated during the accident in Fukushima, accumulation and subsequent detonation of hydrogen gas produced by rapid oxidation can breach the containment structures and result in widespread radioactive contamination [29]. Inerted containment is commonly employed as a hydrogen mitigation system to reduce the risk of hydrogen combustion.

By comparing code predictions of the hydrogen generation during the severe accident progression, insight is given in the complex oxidation processes and differences in the models involved. Hence, hydrogen generation is a good measure to address modeling differences when performing code comparison.

1.4 Probabilistic Safety Analysis

Probabilistic Safety Analysis (PSA) considers the probability, progression and consequences of equipment failure or transient conditions by deriving numerical estimates that provide a consistent measure of the reactor safety [30]. PSA is commonly divided into three different levels, which are briefly described in Table 1.
Table 1. Description of PSA levels

<table>
<thead>
<tr>
<th>PSA</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>Risk assessment of core damage by identifying sequences of events that may lead to loss of core structural integrity and fuel failure</td>
</tr>
<tr>
<td>Level 2</td>
<td>Level 1 + investigation of containment behavior and evaluation of the radioactive products after plant damage and quantification of the release to the environment</td>
</tr>
<tr>
<td>Level 3</td>
<td>Level 2 + evaluation of radionuclide distribution and the off-site consequences associated with source term release on public health and environment</td>
</tr>
</tbody>
</table>

1.4.1 Core damage/plant damage classification

In PSA level 1, core damage states for Nordic BWR’s are usually divided into different categories which specifies the cause of the accident [31]. Possible causes are:

- HS1: Failure to shut down reactor
- HS2: Inadequate delivery of make-up cooling to reactor
- HS3: Loss of residual heat removal capabilities
- HS4: Overpressure of the primary system
- Overpressure of the containment

In addition it is defined whether the accident takes place during a low (L) or high (H) pressure scenario and also if the core damage occur early (T) or late (S) with respect to the timing of the initiating event. For instance, take the combination HS2-TL4 into consideration (the scenario evaluated in this study). The cause of core damage is due to inadequate delivery of make-up coolant i.e. failure of the ECCS (both the high-pressure auxiliary feed water (AFW) and low-pressure system). A low reactor pressure is maintained, which indicates that the automatic depressurization system (ADS) is successfully initiated. Furthermore, core damage occurs early after the initiating event, which in this case is a SBO. The last digit included in the combination is simply there to distinguish similar sequences from each other.

The major contributors to the core damage frequency (CDF) are according to Figure 3, HS2 and HS3 failure modes. Core damage due to inadequate core cooling (HS2 failure mode) contributes to about 60% of the total CDF.
1.4.2 Description of safety systems

A long-term SBO refers to the complete loss of offsite power and on-site emergency AC-power systems (diesel generators) without recovery. When a power plant is left completely without power supply except from battery backups, all manual actions regarding recovery and consequence mitigate systems fails to initiate. The capability to cool the core will therefore depend on the availability of those systems not requiring AC power and their capability to recover the core before battery depletion occurs. Hence, SBO is one of the most challenging accidents for BWR’s and the consequences could be severe, as illustrated at Fukushima.

Relevant safety systems implemented in the MELCOR Nordic BWR model in PSA level 1 and 2 are briefly presented below. However, in the SBO transient being simulated (description provided in section 2.2.1) the majority of the safety systems are unavailable.

- System 354: Scram, the hydraulic actuating power shut-off system gives fully insertion of all control rods within a few seconds after initiation. This rather complicated control rod system is not modeled in MELCOR. Instead fission power is decreased (during 3.5 s) by a tabular function and scram condition, in this case loss of power, is applied as a control function.

- System 314: Pressure control and relief system has several functionalities and is able to operate with only battery backups. Opening of SRV’s (system 314TA) provides instant depressurization of the primary system after scram by discharging steam to the WW. The ADS (system 314TB) is initiated on low water level signal to provide a pressure decrease sufficient for the low pressure injection sources (ECCS) to be activated. Another functionality of the ADS is to maintain the pressure on a desired level. In MELCOR the
different valves are modeled as one flow path and control functions are applied to obtain the desired fractional flow area with respect to reactor pressure.

- **System 321**: Residual heat removal system (RHRs) removes heat from the containment by circulating water from the WW through a heat exchanger. The cooled water is then sprayed into UDW and/or WW, thus a reduction in pressure is obtained by steam condensation. The RHRs was recently implemented in the MELCOR Nordic BWR model [6].

- **System 322**: Containment heat removal system (CHRs) reduces the containment pressure by spraying the UDW. In addition, aerosols are washed out. It also provides cooling of the suppression pool by recirculation water from WW through a heat exchanger and then sprays it back into the pool. In MELCOR flow paths with specified flow areas are applied to simulate the desired flow rate.

- **System 322O**: Containment heat removal with water from an independent (“Oberoende” in Swedish) external source (firewater system) is used to spray the containment as a last emergency measure. Water regulation is provided in order not to damage the containment.

- **System 323**: The low pressure coolant injection (LPCI) is part of the emergency core cooling system (ECCS), which provides water injection into the DC to facilitate reflooding in the bottom of the core. The ECCS was recently implemented in the MELCOR Nordic BWR model [6].

- **System 327**: Auxiliary feed water system (AFW) is the high pressure system of the ECCS, which inserts water into the DC. Cooling water is taken from the condensate storage tank and WW. It has a lower capacity to handle large losses of water compared to the LPCI system but can operate without pressure relief. The AFW system was recently implemented in the MELCOR Nordic BWR model [6].

- **System 358**: Lower drywell (LDW) flooding from WW to LDW is initiated in an early phase of the accident to fill the cavity and provide debris cooling when vessel breach occurs.

- **System 361**: Containment venting system (CVS) via atmosphere is the ultimate pressure relief directly to the ambient surrounding when the internal containment pressure rises above the containment failure limit.

- **System 362**: Containment venting with multi venturi scrubbing system (CVS MVSS) provides a controlled filtered release below the failure limit of the containment that suppress the amount of radioactive aerosols escaping to the environment.
1.5 Models in MELCOR

The following section contains brief descriptions of the input parameters and models used in MELCOR 1.8.6 related to the in-vessel melt progression. The most important parts are hereby summarized, the reader is referred to the MELCOR User’s manual [15] and Reference manual [32] for complete descriptions of the mathematical models applied.

1.5.1 Core structure properties

In MELCOR the structures defining the core are divided into three different groups depending on the ability of supporting itself and other constituents e.g. debris. The control rods are modeled as Non-supporting structure (NS), which can support nothing but itself. NS structure in a cell will collapse unless there are either intact NS or intact supporting structure (SS) immediately below it. The other type is Supporting structure (SS), which cannot only support its on load but also structures in the cell located above e.g. the core support plate and control rod guide tubes (CRGT’s). There is also a third option available, Other structure (OS) that is useful if neither NS nor SS suites the desired purpose and logical user-defined control functions are used instead to determine the failure criteria.

Several options are available for SS applied in each core cell. The choice affects the treatment of support ability, failure criteria and the consequences of failure. The different SS modeling options suitable for BWR’s modeling are summarized in Table 2.

Table 2. Supporting structure (SS) modeling options

<table>
<thead>
<tr>
<th>SS option</th>
<th>Supporting ability</th>
<th>Consequence of SS failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLATEB</td>
<td>Can initially support itself and particulate debris but its presence is required to transfer weight from fuel assemblies and canisters to COLUMN structures located below</td>
<td>SS capability to support particulate debris is removed; intact fuel and canisters can continue to be supported by COLUMN below. Structure remains intact until it melts</td>
</tr>
<tr>
<td>COLUMN</td>
<td>Can initially only support itself but through the mediation of PLATEB it is also able to take the load from fuel assemblies and canisters</td>
<td>SS is converted to particulate debris along with anything supported by PLATEB even though it might be intact structures</td>
</tr>
<tr>
<td>ENDOCL</td>
<td>Equivalent to COLUMN except that it is considered self-supporting</td>
<td>SS is converted to particulate debris along with anything supported by it even though it might be intact structures</td>
</tr>
</tbody>
</table>
In the MELCOR Nordic BWR input, the SS defined for all cells in lower plenum is COLUMN i.e. the primary support of the core represented by CRGT’s. As stated in Table 2, any structure defined by COLUMN must have a structure PLATEB above in order to support fuel assemblies and canisters. Thus, the cells representing the core support plate are defined as PLATEB. The bottom level of COLUMN is assumed to be self-supporting and therefore treated equivalently to the ENDOCL option. Default failure criteria of SS components are critical thickness (default 0.1 mm) and over-temperature i.e. when transition to plastic behavior for steel occurs (1273.15 K). In MELCOR Nordic BWR input, the default has been overwritten by a stress-based modeling. Failure upon both stress (yielding or buckling) and over-temperature is not possible to model simultaneously within one cell.

1.5.2 Debris formation and configuration

In MELCOR the degradation of core materials is calculated individually for each cell at each time step. Detailed assessment of the debris composition and temperature is therefore obtained within each core cell. The core degradation model treats eutectic reactions that lead to liquefaction below normal melting points. However, eutectic interactions are not explicitly modeled and instead melting temperatures are adjusted to capture these interactions [13]. Beside relocation by melting and candling, core materials can also fail mechanically. When core components melt, candling usually occurs immediately. The exception is molten metal (Zircaloy and steel) that can stay held up behind oxide shells until it breaks. Conglomerate debris is the result of candling to cooler regions where molten material resolidifies and becomes an integral part on the intact components. Intact components are immediately converted into particulate debris whenever the support is lost (see section 1.5.1) or whenever the remaining thickness of unoxidized metal is reduced below a critical thickness (default 0.1 mm). Whenever the structural support from the CRGT’s in the lower plenum is lost, all core components located above (except the core plate itself if still intact) within the entire radial ring is instantly turned into particulate debris. Thus, the radial nodalization and subsequently core mass distribution have a major impact on the relocation process in MELCOR modeling. Fuel rods (fuel pellets and cladding) are treated somewhat differently. Upon cladding failure, the radionuclides in the fuel-cladding gap are released. Failure occurs either a temperature criterion is exceeded (default 1173 K) or when the geometry is lost due to candling or oxidation. Oxidized rods are assumed to remain the integrity until melting temperature of either the cladding (2500 K) or UO₂ (3100 K) is reached, thereafter the rods are converted into particulate debris. It is assumed that the gap inventory for the entire ring is released when cladding failure occurs.

Both in the core region and lower plenum, particulate debris is treated as a porous bed with a user-defined particle size (assumed spherical) and porosity. In the MELCOR Nordic BWR model, the default porosity of 30 % had been replaced with 25 %. This value deviates significantly from a porosity of 40 % obtained experimentally (see section 1.3.2).

Furthermore, two distinct stratified molten pools, oxide and metallic, are allowed to take form in the core and lower plenum. Molten pools are formed as candling molten material is blocked due
to intact structural material or particulate debris beds. Local blockages of refrozen material are assumed to represent crusts by occupying available space for downward relocation of molten materials, see Figure 4.

![Intact Conglomerate](image)

Figure 4. Flow blockage for a cell predicted by the candling model [32]

In the absence of local blockages, the molten pool can relocate into the interstitial volume of particulate debris and be transformed into conglomerate debris. In the cavity, properties of crusts thickness etc. are explicit modelled but not in the core and lower plenum. The oxide pool is assumed to be denser and can therefore displace the metallic molten pool volumes. Contiguous volumes of physical molten pools are uniformly mixed by convection and therefore assumed to have a uniform temperature, material and radionuclide composition.

In the end of the in-vessel melt progression, all debris (conglomerate, particulate and molten pools) is accumulated in the lower head. Penetration failure is not modeled as a mechanism for vessel failure, only gross creep rupture. Vessel breach occurs either when temperature in lower head node reaches critical temperature (default 2000 K), differential pressure exceeds defined maximum (default 20 MPa) or Larson-Miller creep-rupture exceeds failure limit (default 1 kPa). When any of the failure criteria is met, the radial rings assume to fail instantly and all the debris located above is immediately ejected into the water-filled cavity.

### 1.5.3 Oxidation of Zircaloy, Steel and B₄C

Oxidation of core components is an important contribution to hydrogen production and core heat up (see section 1.3.3). For each intact structural component user-defined Zircaloy (cladding and canister) and steel (support plate and CRGT’s) surface areas are used in the oxidation calculations. In the temperature range of 1100-9900 K oxidation is modeled for Zircaloy and steel. Modeling of a Zircaloy oxide shell disable relocation of molten material as long as the oxide thickness is greater than 0.01 mm and component temperature is below 2400 K. For B₄C oxidation the threshold temperature is set to 1500 K, which is when the eutectic interaction with the stainless steel control rod clad assumes to start. For the fuel, it is assumed that the release rate of each fission product is proportional the fuel oxidation rate. Furthermore, B₄C reaction is assumed not to begin until the intact steel control blade failure fraction is reduced below 0.9 and the maximum fraction of B₄C that may be consumed by oxidation is limited to 0.02. Oxidation of both particulate and conglomerate debris is taken into consideration for debris temperatures
above 600 K. The rate of heat transfer from the debris to the water is determined primarily by the interfacial surface area, which is calculated from the particle debris size and total mass. The effect of conglomerate debris on intact structures is factored in the calculations. Moreover, MELCOR calculates oxidation of the unquenched surfaces below the pool surface. The necessary steam is assumed to come from the gas film present between the hot surface and the pool. In the simulations performed, steam oxidation is not considered until all oxygen is consumed. The effect of steam and oxygen starvation and flow blockages are simulated explicitly considering unblocked flow areas within the control volumes. The Low Pressure Molten Ejection (LPME) is applied in the current model which does not consider oxidation of metallic elements on the ejected debris to the cavity.

### 1.5.4 Decay heat calculations

Several options are available for decay heat estimation. MELCOR does not treat each decay chain explicitly since that would be too computationally costly. Instead the radionuclides (101 elements) are grouped with elements having similar properties and 16 classes are defined (e.g. halogens and alkali metals) among these, 29 elements are treated as major contributors to the decay heat. Fission products are tracked at each time step and the decay heat is calculated for each class by using pre-calculated tables obtained from a SANDIA-ORIGEN run. Instead of tracking 29 elements and determine the mass inventory at each time step, the option currently used is to calculate the decay heat power for the entire core. With this option, MELCOR uses tables from the ANS standard (which also is applied in MAAP) that prescribe the decay heat power from fission products resulting from the three major fissionable nuclides $^{235}$U, $^{239}$Pu and $^{238}$U. The ANS standard assumes that the energy release per fission is independent of time and depends upon the neutron flux energy spectrum and the composition of the reactor core.

In MELCOR the whole core power, $P_{wc}$, is determined for ANS standard by the expression given in Equation (1).

$$P_{wc}(t) = M_{user} G(t) \sum_{i} \frac{P_i F_i(t,T)}{Q_i} + P_{dHE}(t, T)$$  \hspace{1cm} (1)$$

Where,

- $M_{user}$ multiplier (default 1.0)
- $G(t)$ neutron capture correction factor
- $t$ time since shutdown [s]
- $i$ index for fissioning nuclides: $^{235}$U, $^{239}$Pu and $^{238}$U
- $T$ irradiation time [s]
- $P_i$ power from fissioning of nuclide $i$ [W]
- $F_i(t,T)$ decay power due to nuclide $i$ [MeV/fission]
- $Q_i$ energy per fission of nuclide $i$ [MeV/fission]
- $P_{dHE}$ decay power from $^{239}$U and $^{230}$Np [W]
The decay power $F_i(t,T)$ is found by logarithmic interpolation between given points in ANS tables and $G(t)$ and $P_{dHE}$ are obtained from ANS standard calculations. The effect of neutron capture is accounted for in the standard until $10^4$ s after shutdown, thereafter another more conservative estimate is used, which causes a discontinuity of the decay power curve at this time. Moreover, the irradiation time, $T$, and the fission power, $P_i$, from the major fissioning nuclides $^{235}$U, $^{239}$Pu and $^{238}$U are user-specified inputs. The power distribution applied in the MELCOR Nordic BWR model is 2524.43 MW, 1211.42 MW and 164.153 MW for $^{235}$U, $^{239}$Pu and $^{238}$U respectively. These values were obtained by linearly scaling of the defaults to suit the power of 3900 MW.

### 1.5.5 Maximum time step

The user-imposed maximum time step is recommended to range from 5 to 10 s during the portion of an accident sequence dominated by in-vessel thermal-hydraulics and core melt progression. However, many MELCOR models will reduce the time step to lower values when needed. Very rapid phenomena, certain phenomenological events, or numerical problems encountered by the code may necessitate use of a smaller maximum time step for portions of the transient. As a result, the MELCOR code is somewhat dependent on the skill of the user to select proper time steps until additional automatic time step controls are developed. The time step applied in the MELCOR Nordic BWR model varies from 0.05 to 0.5, which is significantly smaller than the recommended size. The impact of alterations in the maximum time step is presented in section 3.3.2.

### 1.6 Review of previous comparisons between MELCOR and MAAP

Performing code comparison between MELCOR and MAAP to identify differences in prediction of the severe accident progression and address uncertainties in modeling has been of interest, especially when new code versions have been released. Even though different reactor types, initiating events, code versions and phenomena of interest (in-vessel or ex-vessel phenomena etc.) have been applied and studied, differences in modeling can still be addressed independently of the specific scenarios being simulated.

In a comparison performed with MAAP4 and MELCOR 1.8.5 of a SBO in a Westinghouse PWR [20], MAAP predicted a later timing of core uncovery, which delayed the timing of subsequent events. The difference was explained by the fact that core uncovery in the MELCOR is based on collapsed water level whereas in MAAP the two-phase level is used. Furthermore the study concluded that if the input decks in both codes were carefully created and made as similar as possible with consistent conditions, the results were very similar in terms of thermal-hydraulic and core degradations response [20]. Since the early hydrodynamic response shown very good agreement, this suggest that the factors influencing the overall mass and energy balance prior to
the onset of core damage are calculated in a similar way [14]. However, after core support structure failure, a large difference in hydrogen generation was observed. As molten material slumps into the lower head, additional hydrogen was generated in MELCOR but little in MAAP [20]. The same observation was made in a study of a SBO in a General Electric BWR using MELCOR 1.8.3 and MAAP4 [14]. This was explained by the prediction of rapid metallic oxidation in MELCOR as the debris relocated in the residual water in the lower head, which was not modeled in MAAP [14]. A publication of a SBO sequence of the Maanchan PWR in Taiwan using MELCOR 1.8.5 and MAAP4 [33], explained how the resulting material geometry in MAAP limited the extent to which unoxidized metallic components are exposed to steam generated, thereby limiting hydrogen generation.

Although the prediction of debris characteristics and composition in lower plenum was not compared in any of the above mentioned studies, significant differences in the models of debris heat transfer within the lower head were discussed. These differences were expected to explain why the time between core support plate failure and vessel breach deviated between MELCOR and MAAP [14], [33].

Over all, previously performed studies conclude that the important severe accident phenomena including core uncover, cladding oxidation, cladding failure, debris relocation to the lower plenum, and vessel head failure give similar results [33]. Any discrepancy in prediction of decay heat was not stated in any of the studies. The minor discrepancies seen in various timing of phenomena were within the uncertainties of the code numerical computation and physics models [20].

Compare to the aforementioned studies in which the confidentiality of MAAP modeling limited the possibility to explain differences in results, a recently released comparison between MELCOR and MAAP calculations of the Fukushima accident in Unit 1 reveals additional information about models applied in MAAP [13]. The study is the first publicity available document containing detailed description of the in-vessel core melt progression in MAAP and explanations to key modeling differences compared to MELCOR. Most recent code versions were used in the comparison, MELCOR 2.1 and MAAP5. Some key modeling differences of the in-vessel melt progression presented in the paper are summarized below:

- MAAP explicitly models eutectic interactions occurring during core degradation which MELCOR does not. As a consequence, all Zircaloy is assumed to fail at the same temperature in MELCOR and the eutectic interaction between stainless steel and Zircaloy is not represented.
- MAAP identified shroud failure prior to core support plate failure due to radial spreading of molten debris in core region. MELCOR modeling does not include shroud failure.
- MAAP simulates a large core mass held-up on the core support plate and at the time of support plate failure debris in all radial rings are affected. Hence, MAAP predicted a very rapid relocation of debris to lower plenum compare to MELCOR, which simulates a more gradual relocation and failure of the support plate affects the rings individually.
Hold-up on CRGT’s is, compared to MELCOR, not presented in MAAP. Instead debris is assumed to relocate directly to the lower plenum before interacting with the lower plenum structures.

In MAAP, molten debris is allowed to relocate into open volume in the particulate debris and subsequently reduce the porosity and effective heat transfer area. In MELCOR, molten debris that freezes into a particulate debris bed is assumed to increase the volume of the fixed-diameter particulate spheres and subsequently increase the heat transfer area.

In MAAP the open flow area was reduced below 10 % after loss of core geometry, compared to 60 % in MELCOR. Flow blockages significantly affect core oxidation and subsequently promote much more hydrogen generation in MELCOR (4 times more compared to MAAP).

In MAAP approximately 66 % of the original core mass formed a molten oxidic pool in lower plenum prior to vessel breach compare to MELCOR where oxide and metallic pools are negligible.

In the specific sequence simulated, MAAP predicted failure of all fuel assemblies compared to MELCOR where the two outermost rings remained intact. This subsequently effected the debris mass relocation, hydrogen generation etc.

MAAP assumes debris is ejected into lower plenum as a jet with limited interaction with the water.

Differences in results in lower plenum do not entirely reflect model differences associated with lower plenum physical processes. The differences in nature of the degraded core inside the core region dominate the difference in lower plenum modeling.

MAAP and MELCOR models of lower plenum core debris are conceptually different that ultimately results in distinct ways in which debris heat transfer is characterized. In MAAP, the lower plenum is nodalized in term of debris constituents. The constituents are layered and each can vary in volume based on the amount of core material that has formed each type of lower plenum debris. The transition from a particulate debris bed to distinct molten pools and stratified metal layers are not directly and mechanistically modeled. Thus, the terminal form of the lower plenum debris is pre-determined in MAAP. In contrast, MELCOR represents debris in terms of a set of axial and radial debris nodes occupying fixed sub-volumes in the lower plenum. The type of debris in a node is determined based on the type of debris that has relocated into it and its temperature.

MAAP calculates lower head wall heat up shortly after debris slumping to the lower plenum compare to MELCOR which predicts heat up first after all water in the lower plenum has boiled away. Hence, the lower rate of debris slumping to the lower plenum results in a much slower depletion of lower plenum water than found in the MAAP simulation. Convective heat transfer from the oxidic molten pool is the primary process by which decay heat is rejected to the lower head wall in MAAP.
1.6.1 Previous development of the MELCOR Nordic BWR model

The original input deck of the MELCOR Nordic BWR model was developed in 2006 by Lars Nilsson under contract from Swedish Nuclear Power Inspectorate (SKI) [34]. An input model of Nordic BWR’s was created for MELCOR version 1.8.5 through a comparison with existing models in MAAP. Further development of the input was done at KTH in connection with a power upgrade from 3300 MW to current 3900 MW [35]. Recently work performed at KTH is related to SBO transients with varying degree of safety system recovery (ADS and ECCS) and the impact on relocation and vessel breach is examined using MELCOR version 1.8.6 [4], [31].

The outcome of the first general comparison between MELCOR Nordic BWR model and MAAP results carried out at LRC showed several differences and issues related to the relocation progression [5]. In further comparison, several issues were solved and safety systems (ECCS, AFW and RHR) implemented which enabled more scenarios to be simulated and compared to MAAP [6]. The investigated scenario was in both aforementioned comparisons a SBO (MAAP Case 6). The main outcomes from these studies are summarized below:

- By changing decay heat model from ORIGEN to ANS, MELCOR still predicted less decay head than MAAP but the difference was decreased from 37 % to 13 %.
- A pressure spike was obtained in MAAP due to steam production after molten material had entered the lower plenum which was not seen in MELCOR.
- Timing of vessel breach occurred earlier in MELCOR (4.0 h) compared to MELCOR (7.0 h).
- By increasing heat transfer coefficients, quenching of the debris when entering the water filled cavity was implemented in MELCOR.
- Higher pressure in containment caused earlier opening of the Containment Venting System (CVS) in MAAP (4.6 h) compare to MELCOR (9.9 h).
- MELCOR predicted a continuous generation of H₂ during relocation, while in MAAP generation is limited to the timing of start of relocation to lower plenum and debris falling into the cavity. The total amount of generated H₂ was similar.
- MAAP predicted a large hydrogen increase as hot debris enters the water-filled cavity, a phenomena not seen in MELCOR.
- Safety systems (ECCS, AFW and RHR) were implemented in the MELCOR model.
- MVSS model (Scrubber) was modified for closer resemblance with reality.
- No Molten Core Concrete Interaction (MCCI) was predicted by any of the codes.

In addition, there were a few recommendations for further work in Nilsson’s study [34] which yet not have been taken into consideration. Suggestively, special attention should be paid to the debris modeling parameters i.e. particle size, porosity and velocity of the falling debris.
1.7 Summary about the state-of-the-art

The above review of the in-vessel relocation phenomena shows the complexity of the process and the lack of advanced understanding associated with the phenomena involved in the accident progression. As a consequence, inherent modeling uncertainties arise within the computer codes. Besides the models themselves, code input has been identified as another important source of uncertainty in code comparison.

Several comparisons have been done in the past for a variety of reactor designs and accident sequences to address modeling uncertainties in MELCOR and MAAP. However, the prediction of core degradation and debris relocation has not been compared until recently. In EPRI’s code comparison of the Fukushima accident valuable insights in key modeling and approaches applied within two codes were compared and the impact on the result addressed [13]. Information about MAAP5 modeling that previously has been strictly confidential is now official. Nevertheless, the code versions applied in EPRI’s comparison are the most recent and because of updates, the conclusions may not be directly applicable to older version used within the current study.

So far, limited comparisons have been performed between the MELCOR Nordic BWR model and MAAP. Several unresolved issues e.g. prediction of decay heat level and hydrogen generation remain unexplained. In addition:

- The input has not been compared to MAAP data since the original MELCOR model was created in 2006. Development of the MELCOR model have been done in parallel and updates been made separately. Hence, the inputs have not been carefully compared to MAAP and therefore uncertainties might arise from differences in input.
- The prediction of debris characteristics and composition in lower plenum has not been studied and compared to MAAP.
- Recommendations for further work in Nilsson’s study regarding particle size, porosity and debris falling velocity have yet not been evaluated.
- The time step size has not been identified as a source of uncertainty and therefore the impact on the result has not been evaluated.
1.8 Goals and Tasks

The main objective with this study is to identify possible reasons for discrepancies between MELCOR and MAAP results of the in-vessel melt progression during a SBO. Differences in timing of key events in the calculated accident progression or other important aspects of the severe accident behavior e.g. debris formation shall be identified. Modeling uncertainties caused by discrepancies in inputs should be reduced and the impact of these differences be analyzed. Furthermore, the study should strive towards an increased knowledge of MAAP and MELCOR calculations, and to find possible explanations of differences in prediction of following accident phenomena:

- Core degradation and relocation progression
- Core support plate failure
- Resulting debris mass and composition of the debris in the lower head
- Prediction of hydrogen generation

In order to reach the objectives, the present work could be divided into four tasks:

i) Develop a technical approach for comparison of complex severe accident analysis codes.

ii) Compare the current MELCOR Nordic BWR input to available data in MAAP to address difference in input e.g. nodalization, input parameters and failure criteria.

iii) Update the current MELCOR model in accordance to MAAP and compare the results to address discrepancies and uncertainties in modeling of the in-vessel accident scenario.

iv) Evaluate factors contributing to the uncertainty in prediction of the core degradation and relocation progression.
2 Approach and Methodology

2.1 Technical approach

In order to enable comparison between MELCOR and MAAP input and calculations, following technical approach was developed:

i) Identify interesting scenarios in MELCOR and corresponding case/cases in MAAP with respect to initiating event and safety system availability. Choose one scenario for further evaluation. Considering one single sets of sequences is the most worthwhile when studying how modeling of specific phenomena during the accident progression may deviate between computer codes [13].

ii) Identify comparable input and output parameters. Attention must be paid so equivalent parameters are identified. Due to differences in parameters taken into consideration within each of the codes, comparable parameters cannot always be found.

iii) Perform a detailed assessment of the MELCOR input and available MAAP data to identify numerical discrepancies in input parameters and nodalization.

iv) State hypotheses on what results to expect (before performing simulations) based on the knowledge of discovered discrepancies in input and calculation models applied in MELCOR. Observable factors are identified, from which it should be possible to confirm or decline each hypothesis.

v) Reduce modeling uncertainty arisen from code input. Update the MELCOR input decks in accordance to available data in MAAP i.e. make the inputs as similar as possible. Perform simulations and analyze the results.

vi) Investigate the impact of alterations in maximum time step, $dt_{\text{max}}$. Perform additional simulations where $dt_{\text{max}}$ is altered and all other input parameters kept unchanged.

vii) Perform parameters studies in MELCOR to evaluate the sensitivity for each of the major discrepancies discovered in input parameters in task iii). Analyze the result with focus on the observable factors.

The existing MELCOR Nordic BWR input decks were used to perform simulations for comparison with results obtained in MAAP. Valuable information about MELCOR models was found in the User’s guide [15] and Reference Manual [32]. A summary of the most relevant parts for from the manuals are presented in section 1.5. Moreover, the report of the development of the original MELCOR Nordic BWR model made by Nilsson [34] was useful and its content discussed several times throughout this report.
Due to secrecy reasons, all figures presented in the report lacks numerical y-labels and no absolute values from MAAP calculations are displayed. All confidential data is collected in Appendix B and is only available if permission is given. To enable numerical comparison within the report, values in MELCOR are normalized to the values obtained in MAAP.

2.1.1 MELCOR simulations

MELCOR 1.8.6 was employed in the present study. Since the original model has been updated by KTH and LRC in parallel, a merged input was created for this study. A steady-state run was made for 300 s in order to achieve stability and good starting point for transient simulations. Thereafter simulations were performed for a duration of 40 000 s (11.1 h). This time was sufficient to enable evaluation of the whole degradation progression from core heat up to vessel failure. A plotting frequency of 10 s was applied.

In the meantime of the project progression, the input decks were updated to suite MELCOR 2.1. Conversion to the new version is recommended since several improvements of the models related to core degradation have been done. However, the results presented in this study are obtained in version 1.8.6.

2.1.2 MAAP simulations

Simulations in MAAP 4.0.6 were already performed beforehand (in 2008) and the result was available in text files. Moreover a tabular file was available, containing more detailed data for e.g. core node temperatures, decay heat contribution from each radionuclide group etc. The frequency for this tabular file is determined in the input file and for the current simulations, every 2 hours had been chosen. Since the possibility to change input parameters and run new simulations did not exist, parameter studies could not be performed.

All MAAP simulations have a duration of 200 000 seconds. A plotting frequency of 2 seconds was applied in time regions very rapid phenomena were expected or else the frequency was set to 300 seconds, which is significantly coarser than in MELCOR.

2.1.3 Limitations in available MAAP data

No MAAP manuals were provided due to confidentiality, therefore this study lacks comparison of code models that otherwise could have been useful to explain differences in the obtained results. Available data was often taken out of it context and the parameters lacked detailed descriptions. Hence, interpretations needed to been made in the process of finding equivalent and comparable parameters to MELCOR. In addition, the format and nomenclature often differ between the two codes. As a result, it can be difficult to determine whether the two codes calculate different values for the same parameter because, in fact, the “same” parameter can represent slightly different quantities within each code i.e. the definition of “core region” might not refer to the same core volume.
2.2 Scenarios available for comparison

In total, data from 41 scenarios are available in MAAP with SBO transient or LOCA as initial event. Different combinations of safety system functionality are evaluated in each of the cases to access estimation of the source term used in PSA level 2 analyses. Four interesting cases with SBO as initiating event were identified in MELCOR, see Table 3. Further description of the safety systems involved are provided in section 1.4.2.

Table 3. Interesting SBO transients to analyze in MELCOR

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Initial event and safety system availability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case A:</strong></td>
<td>SBO with successful opening of SRV (314TA), failing initiation of AFW (327) and ADS (314TB)</td>
</tr>
<tr>
<td>(HS2-TH1)</td>
<td></td>
</tr>
<tr>
<td><strong>Case B:</strong></td>
<td>SBO with successful initiation of 314TA and 314TB, failing initiation of 327 and low-pressure ECCS (323)</td>
</tr>
<tr>
<td>(HS2-TL4)</td>
<td></td>
</tr>
<tr>
<td><strong>Case C:</strong></td>
<td>SBO with successful initiation of 314TA, 314TB and 323, failing containment heat removal (322)</td>
</tr>
<tr>
<td>(HS3-SL4)</td>
<td></td>
</tr>
<tr>
<td><strong>Case D:</strong></td>
<td>SBO with successful initiation of 314TA, 314TB, 323 and 322</td>
</tr>
<tr>
<td>(Core recovery)</td>
<td></td>
</tr>
</tbody>
</table>

In Figure 5, a simplified block diagram is presented, which includes what safety systems are activated in each of the four cases A-D in PSA level 1. Horizontal arrows represent successful initiation while vertical mean failure of that particular system. Core damage occurs in all cases except case D, where all necessary safety systems are successfully activated and therefore the core is recovered. Case D is not available in MAAP since core recovery is not simulated. For each of the PSA level 1 sequences A-C, there are multiple paths to plant damage which are analyzed in PSA level 2. A complete overview of Cases A-C and corresponding scenarios available in MAAP is presented in Appendix A.
2.2.1 Description of selected scenario

For comparison, MELOR Case B, equivalent to MAAP Case 6 was chosen for further investigation of the in-vessel melt progression. The same scenario has been evaluated in previous comparisons with MELCOR Nordic BWR model (see section 1.6.1) and therefore selected in order to attempt to solve the remaining unresolved issues. Figure 6 below, which is the continuation of Figure 5, represents the block diagram leading to plant damage state in the HS2-TL4 sequence. Also here, horizontal arrows represent successful initiation while vertical mean failure of that particular system. Success of system 361 (CVS via atmosphere) means that the reactor containment is successfully isolated i.e. rupture disk remains intact.
An overview of the accident progression and initiation of the different safety systems (further description provided in section 1.4.2) is presented below:

- A SBO leaves plant without AC power, battery backup are depleted after 48 h.
- Scram is initiated (system 354) at t=0 s with a duration of 3.5 s until completion.
- Reactor pressure is initially kept at 70 bar by the opening of SRV (system 314TA).
- The ADS (system 314TB) is activated on low water level L6 (-1.0 m) below top of active fuel (TOAF) with a delay of 2 minutes and depressurization is obtained by discharging steam through relief values to WW.
- Boil down and core heat up due to failure of ECCS, low-pressure core spray (system 323) and high pressure injection AFW (system 327).
- LDW is flooded (system 358) to provide cooling of the melt in case of vessel breach and to protect the penetrations and delay radioactive release.
- Core support failure and relocation to lower plenum occurs.
- Inadequate cooling of debris causes temperature increase of the lower head segments and eventually vessel failure.
- Quenching of debris takes place when molten material interacts with the water-filled cavity.
- CVS initiated by automatic opening of MVSS (system 362) and the amount of radioactive release to environment is reduced in the scrubber during pressure relief.

### 2.3 MELCOR Nordic BWR thermal hydraulics

The MELCOR Nordic BWR model has a total thermal power output of 3900 MW. The core consists of 700 fuel assemblies of SVEA-96 Optima2 type. The primary system comprises 27 control volumes (CV), connected with 45 flow paths (FL) and 73 heat structures (HS). The nodalization is originally defined in accordance to the model used in MAAP [34]. Figure 7 represents the containment nodalization consisting of the main volumes: UDW (CV220), LDW (CV210) and WW (CV250). The environment is defined as CV900. Elevations are defined with the interior surface of the RPV bottom as reference point. In Figure 8, the vessel nodalization for hydrodynamics is presented. The core is represented by CV120 and a bypass volume CV130 is specified to represent the interstitial volume between fuel assemblies.

The vessel comprises a 6-ring, 14-axial level control volume geometry and the core region is represented by a 5-ring, 8-level model in accordance to Figure 9. Numbering is applied from bottom to top respective inside to out. Level 1 represents the lower head, level 2-5 the lower plenum and level 6 the location of the core support plate, with a thickness of 8.5 cm. The inactive inlet is represented by level 7 and core exit by level 14. The axial levels are unevenly distributed likewise the radial ring division. The three innermost rings contain 176 fuel assemblies each, the fourth ring 80 and the outermost 92.
Figure 7. Containment nodalization in MELCOR Nordic BWR [34]

Figure 8. Vessel nodalization in MELCOR Nordic BWR [34]
Figure 9. MELCOR axial and radial distribution [34]
3 Results and Discussion

In the section below the discovered discrepancies in input between MELCOR Nordic BWR and MAAP data are discussed. Hypotheses are stated in order to plan the analysis. The results obtained from the simulations of the selected SBO scenario are compared and differences in prediction of core degradation analyzed. In addition, the results from the parameter studies are presented and the impact of the maximum time step is evaluated.

3.1 Discrepancies in nodalization and input parameters

When the input decks of the MELCOR Nordic BWR model was compared to available data in MAAP, several differences were discovered both in nodalization and other input parameters, which had not been taken into consideration in previous comparisons. In Appendix B, all discrepancies are summarized.

3.1.1 Core nodalization

In Figure 10, a schematic sketch of the axial nodalization in MELCOR respective MAAP is presented. In MAAP data the only known elevation is the bottom of axial level 1 and the heights of each of the 13 axial levels. No information is available regarding which level that represents the support plate. Subsequently, the thickness of plate in MAAP cannot be confirmed, therefore two different interpretations could be made, either (a) or (b). In interpretation (a) the core support plate is located below the defined axial levels 1-13 with an unknown thickness. In terms of axial heights, interpretation (a) agrees well with the nodalization applied in MELCOR. Interpretation (b) on the other hand, is based on the core mass distribution available in the MAAP data. Nodes in the lowest axial level (level 1) comprises only steel and should therefore represent the support plate, while level 2 consists solely of Zircaloy and represent the inactive inlet. However, the thickness of the support plate is significantly larger in interpretation (b) compared to MELCOR (8.5 cm) although the amount of steel on this axial level is considerably less (70 %) compare to the mass assumed in the current MELCOR model. The core support plate and its interface to control rods and fuel assembly is a complex structure and simplification may therefore been made differently in MELCOR and MAAP. If the timing of core support plate differs between the codes, this can indicate difference in thickness of the plate assuming similar failure criteria.
Figure 10. Axial nodalization in core region.
Two different interpretations (a) and (b) are possible in MAAP

Despite the difference in core support plate thickness, the active core comprises 10 axial level in MAAP compared to 6 levels in MELCOR i.e. MAAP has a finer axial nodalization of the core. Since MELCOR applies certain conditions and failure criteria to each cell individually, a finer nodalization could have an impact on the core degradation and relocation progression. Due to the design of the SVEA-96 Optima2 fuel, MELCOR applies an average value of 3.68 m for the heated length [34] while the longest dimension is taken into consideration in available MAAP data. Moreover, the axial levels in the active part of the core are assumed to be evenly distributed in MAAP since no other information about the division was available, but are unevenly distributed in MELCOR. Radially, the core is divided into 5 rings in both MELCOR and MAAP.

As displayed in Table 4, core elevations are 1-2 % less in MELCOR. Due to these differences, the whole core region is shifted approximately 0.1 m upwards in MAAP. Consequently, the initiation criteria for the ADS, which depend on the water level above/below TOAF, will be activated on different heights in MELCOR respective MAAP. In addition, the reference point for elevations within the reactor building in MAAP is way below the actual plant (probably at sea level) and not at the bottom of the vessel as in MELCOR. The relation used when comparing elevations between the codes differs from the one stated in Nilsson’s report [34], the reason for this is unknown.
Table 4. Normalized elevations in core region

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MELCOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOAF [m]</td>
<td>0.99</td>
</tr>
<tr>
<td>Height of active core [m]</td>
<td>0.98</td>
</tr>
<tr>
<td>Elevation bottom of core support plate (interpretation (b)) [m]</td>
<td>0.98</td>
</tr>
</tbody>
</table>

### 3.1.2 Initial core masses

By comparing core cross-sections in MELCOR and MAAP it is seen that the radii division among the five radial rings differs significantly, presented in Figure 11. In MAAP the radial distance from the center increases constantly for each ring which is not the case in MELCOR. Subsequently the fuel distribution among the rings is expected to differ considerably.

![Figure 11. Radial ring division in core](image)

From Figure 12 it can be deduced that all axial cells within each ring contains the same amount of fuel in MAAP (constant mass distribution axially in each ring). Due to the radii division, the fuel mass increases stepwise towards the outer rings. On the opposite, the fuel mass varies axially in MELCOR, small steps within each ring represents different fuel masses in the cells on axial level 8-13. The three innermost rings in MELCOR contain twice the amount of mass compared to the two outer, also presented in Table 5. A complete compilation of the UO₂ mass distribution in MELCOR and MAAP is presented in Appendix B.
According to Table 5, the total fuel mass deviates by approximately 5% i.e. MELCOR Nordic BWR input contains more UO$_2$ than MAAP. The impact of this mass deviation on the relocation progression is analyzed further in section 0.

Table 5. Normalized initial fuel distribution among the rings

<table>
<thead>
<tr>
<th>Ring #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>MELCOR</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.12</td>
<td>0.14</td>
<td>1.05</td>
</tr>
<tr>
<td>MAAP</td>
<td>0.04</td>
<td>0.13</td>
<td>0.19</td>
<td>0.26</td>
<td>0.37</td>
<td>1</td>
</tr>
</tbody>
</table>

By comparing initial core masses in MELCOR Nordic BWR model not only to MAAP but also to the original MELCOR input created by Nilsson [34], insight was given to what extent modifications have been made previously to the model. Since the fuel mass differs by 5% between MELCOR and MAAP it is expected to see a proportional adjustment made in cladding material (Zircaloy). According to Table 6, the total amount of Zircaloy has been kept constant independently of the UO$_2$ increase. The amount of Inconel and B$_4$C is also identical to the original input. The mass of steel in the control blades and in the inlet part has been increased by 3.9 tons and 2.4 tons respectively compared to Nilsson’s input.

Furthermore, the total Zircaloy mass in the core (canister and cladding) is approximately 15% larger in MAAP. A possible reason for the missing Zircaloy mass in MELCOR is the water channel present in the center of each fuel assembly. Since there is no input parameter defining the water channel structure in MELCOR, the additional Zircaloy mass has been excluded from the model. Assuming dimensions according to the assembly cross-section in Appendix B, the mass of
the water channel agrees very well with the additional 15% Zircaloy in MAAP. Since oxidation of Zircaloy is a major contributor to the hydrogen generation and heat production during core meltdown, the additional mass is expected to have an impact on the melt progression.

Table 6. Comparison of initial core masses in MELCOR Nordic BWR model, the original MELCOR input [34] and MAAP.

<table>
<thead>
<tr>
<th>Initial core masses</th>
<th>MELCOR BWR 75</th>
<th>MELCOR Nilsson</th>
<th>MAAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>UO₂ (Normalized)</td>
<td>1.05</td>
<td>0.99</td>
<td>1</td>
</tr>
<tr>
<td>Total Zircaloy mass (Normalized)</td>
<td>0.85</td>
<td>0.85</td>
<td>1</td>
</tr>
<tr>
<td>Stainless steel core support plate (Normalized)</td>
<td>1.70 *</td>
<td>1.70</td>
<td>1 **</td>
</tr>
<tr>
<td>Zircaloy in cladding</td>
<td>28 730.5</td>
<td>28 731</td>
<td>-</td>
</tr>
<tr>
<td>Zircaloy in canisters</td>
<td>22 050</td>
<td>22 050</td>
<td>-</td>
</tr>
<tr>
<td>Inconel in spacers</td>
<td>604.6</td>
<td>604.6</td>
<td>-</td>
</tr>
<tr>
<td>B₄C in control rods</td>
<td>1706.9</td>
<td>1706.9</td>
<td>-</td>
</tr>
<tr>
<td>Stainless steel in fuel assembly inlet part</td>
<td>10 115.9</td>
<td>7700.0</td>
<td>-</td>
</tr>
<tr>
<td>Stainless steel in control rods</td>
<td>22 262.4</td>
<td>18 303.3</td>
<td>-</td>
</tr>
</tbody>
</table>

* In axial level 6  
** In axial level 1 in interpretation (b) in Figure 10.

3.1.3 Core power distribution

A comparison of the axial and radial power profiles is presented in Figure 13 respective Figure 14. Axially, MAAP predicts a higher power profile higher up in the active core compare to MELCOR. Radially, MAAP has a flatter profile in the center of the core at a lower power level and a linear decrease in power peaking factor in the periphery of the core. In MAAP, area fractions of each radial ring were given but the radii unknown. Therefore the same outer radius of ring 5 (2.547 m) applied in MELCOR was assumed to determine the radial power profile. Numerical values regarding the core power distribution are presented in Appendix B.
3.1.4 Discrepancies in input parameters

Besides differences in nodalization and initial core masses, some major discrepancies in input parameters were also discovered, which are summarized in Table 7. The particle size of the particulate debris applied in MELCOR Nordic BWR input is 4.77 times the size in MAAP. Since the diameter is used to determine the surface area applied in heat transfer calculations (inverse relationship between heat transfer and particle radius), the deviation in particle size is expected to have impact on the hydrogen generation. Moreover, the velocity of the debris entering the lower plenum after core support plate failure is set to a value much lower in the MELCOR input compared to MAAP. Somehow the default velocity in MELCOR differs between the manuals of 1 m/s [15] and 5 m/s [32], but the applied value in MELCOR is significantly smaller than any of the defaults. One possibility for the choice of such a small velocity was to enhance the debris/steam interaction by increasing the duration of the fall. However, the reason for this huge difference was most likely due to a misinterpretation of MAAP data made by Nilsson when the original input was created. Other differences discovered were the irradiation time and the cladding failure temperature, assumed 87% and 17% higher in the MELCOR model compared to MAAP respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MELCOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial UO$_2$ mass</td>
<td>1.05</td>
</tr>
<tr>
<td>Irradiation time</td>
<td>1.87</td>
</tr>
<tr>
<td>Particle size of particulate debris in lower plenum</td>
<td>4.77</td>
</tr>
<tr>
<td>Fuel cladding failure temperature</td>
<td>1.17</td>
</tr>
<tr>
<td>Debris falling velocity into lower plenum</td>
<td>0.02</td>
</tr>
</tbody>
</table>
3.2 Hypotheses for discrepancies in result

Based on the knowledge gained about MELCOR models and differences within MELCOR and MAAP inputs, a set of hypotheses could be stated on what outcome to expect if the MELCOR input was kept unchanged and the results compared with MAAP. To each hypothesis, an observable factor (output parameter) is identified from which the statement could be proved plausible or not. If more than one hypothesis predicts the same outcome or if the hypotheses are contradictory, later evaluation of the result will indicate what parameter had the most impact. A hypothesis should be valid if other factors are not important or predicted equally in both codes.

The hypotheses (H1-H6) are stated below:

**Relocation**

H1. MELCOR will predict a massive first relocation to lower plenum due to modeling of supporting structures failure and current nodalization i.e. center ring contains large amount of fuel.

   Observable factor: debris mass relocation into lower plenum

H2. MELCOR will predict later relocation to lower plenum because of a higher steel mass content of the core support plate (compared to MAAP interpretation (b) discussed in section 3.1.1)

   Observable factor: time of relocation to lower plenum

H3. MELCOR will predict later fuel rod collapse due to higher failure temperature of the cladding, subsequently core degradation should be delayed.

   Observable factor: intact ZrO$_2$ mass on cladding

**Oxidation**

H4. MELCOR will predict less hydrogen generation because of 15% less initial Zircaloy mass.

   Observable factors: hydrogen production

H5. MELCOR will predict less hydrogen generation due to larger particle size and subsequently smaller surface area of the total debris (smaller area relative to its volume) available for interaction with steam/oxygen.

   Observable factor: hydrogen production

**Decay heat**

H6. MELCOR will predict similar level of decay heat independently of alterations in input of the parameters in Table 7 except for changes in irradiation time since it is included in the whole core ANS standard decay heat calculation in Equation (1).

   Observable factor: decay heat
3.3 Comparison of the SBO transient results

By updating the MELCOR Nordic BWR input in accordance to MAAP (power profiles and parameters specified in Table 7) the inputs were made as similar as possible. However, no geometries were altered in MELCOR i.e. the nodalization and subsequently fuel distribution were kept unchanged. The known difference in prediction of decay heat was not taken into consideration but is instead evaluated as part of the parameter study in section 0. The missing Zircaloy mass (15 %) due to the presence of water channel structures was also not taken into consideration since no such input record is available in MELCOR. However, since the fuel mass was increased by 5 %, the cladding material was added in proportion. Thus, still 10 % difference in initial total Zircaloy mass is present when comparing the results. With a reduction of numerical discrepancies in input, differences in results could be evaluated and uncertainties in modeling be addressed for the chosen SBO scenario (description provided in section 2.2.1).

In Table 8, the timing of key events during the accident progression is compared. Low water level L6 (-1.0 m) below TOAF and activation of the ADS occur earlier in MAAP. A higher level of decay heat (9-10%) could be the reason for faster evaporation and a more rapid water level decrease. In addition, the core is shifted upwards in MAAP relative to MELCOR (section 3.1.1). Since similar initial water levels in the DC are observed (Figure 22), water level L6 will be reached earlier in MAAP due to geometric differences of the defined control volumes. Hydrogen generation starts about 18 min earlier in MAAP, which indicates a more rapid core heat up and thus earlier steam/cladding interaction.

Furthermore, core support plate failure occurs approximately 12 minutes later in MAAP. Thus, the obtained difference in timing opposes hypothesis H2 (see section 3.2). Although available data indicates that the support plate structure comprises 70 % more steel in MELCOR compare to MAAP, a delay in time of failure was not obtained in MELCOR. Hence, hypothesis H2 is declined. This might indicate that the interpretation of the MAAP data of core masses was incorrect, and if similar failure criteria are applied, that the support plate thickness in MAAP in fact is larger than in MELCOR. However, the debris mass in the core region is significantly larger in MELCOR (Figure 18), which may result in a heavier load and subsequently an earlier failure even though the plate thickness is larger. Further evaluation is necessary in order to clarify the difference in core support plate thickness between the code inputs and its impact on the accident progression.

Start of debris relocation occurs 50 minutes after the initiating event in MELCOR, approximately 20 minutes before MAAP. Thereafter the relocation progression is about 60 % faster in MAAP. Thus, the time required for reactor vessel failure to occur after a substantial mass of core debris relocated into the lower head is less in MAAP (4 h) compared to MELCOR (5.8 h). Most likely this arises from differences between the models for debris heat transfer within the reactor vessel lower head, and for structural failure model of the lower head segments. Opening of the CVS is predicted earlier in MAAP (4.6 h) compared to MELCOR (7.9 h).
Hence, the containment pressure is higher in MAAP or different opening criteria are applied. Modeling of the CVS is beyond the scope of this work and is therefore not analyzed further.

Table 8. Timing of key events

<table>
<thead>
<tr>
<th>Event</th>
<th>MELCOR updated</th>
<th>MAAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBO</td>
<td>0 s</td>
<td>0 s</td>
</tr>
<tr>
<td>Reactor shutdown</td>
<td>3.5 s</td>
<td>4 s</td>
</tr>
<tr>
<td>Low water level L4 (+0.5 m)</td>
<td>900 s</td>
<td>736 s</td>
</tr>
<tr>
<td>ADS activation</td>
<td>1630 s</td>
<td>1153 s</td>
</tr>
<tr>
<td>Hydrogen production begins</td>
<td>2370 s</td>
<td>1273 s</td>
</tr>
<tr>
<td>Start of relocation to lower plenum</td>
<td>2970 s</td>
<td>4210 s</td>
</tr>
<tr>
<td>Core support plate failure</td>
<td>5127 s</td>
<td>5839 s</td>
</tr>
<tr>
<td>50% of debris relocated to lower plenum</td>
<td>5497 s</td>
<td>9366 s</td>
</tr>
<tr>
<td>90% of debris relocated to lower plenum</td>
<td>16 022 s</td>
<td>11 324 s</td>
</tr>
<tr>
<td>Vessel failure</td>
<td>21 039 s</td>
<td>14 498 s</td>
</tr>
<tr>
<td>Opening of CVS MVSS (via scrubber)</td>
<td>28 785 s</td>
<td>16 680 s</td>
</tr>
</tbody>
</table>

According to Figure 15, a good agreement of the depressurization of the primary system is observed between MELCOR and MAAP. The pressure drop after pressure relief is more rapid in MAAP, which is due to a higher flow rate according to Figure 16. Further adjustment of the flow rate is needed in order to obtain the same pressure drop as in MAAP. A distinct pressure spike is seen after 6000 s in MAAP. This spike is caused by the first massive relocation to lower plenum followed by an increase in hydrogen generation as hot debris enters the water pool. An increase but no distinct pressure spike is predicted in MELCOR after core support plate failure.

In Figure 17, the maximum fuel temperature in MELCOR is compared to the maximum core temperature in MAAP. The initial temperature is slightly higher in MAAP but the increase during fuel heat up and core degradation is in good agreement until core support plate failure. Thereafter, the temperature drops in MELCOR and at time of completed fuel rod failure, which takes place approximately 3000 s earlier in MAAP, the temperature is three times lower the predicted value in MAAP. The obtained difference in prediction of maximum core/fuel temperature and time of fuel rod collapse indicates differences in fuel rod failure modeling. In MELCOR fuel assemblies collapse at a somewhat lower temperature compare to MAAP [14]. Another possibility for the deviation in result is the fact that different components are plotted and compared (fuel temperature vs. core temperature). Even though the fuel temperature is similar during core heat up, almost 50 % more debris is present in the core in MELCOR as seen in
Figure 18. Differences obtained may arise from the deviation in decay heat or different fuel rod failure modeling.

In Figure 19, the prediction of debris mass in lower plenum is presented. In MELCOR, about six times more debris drips through the core support plate before failure. This indicates dissimilarities in modeling of plate/debris interaction. During the first massive relocation, almost 70% of the total debris mass in MELCOR is instantly ejected into lower plenum, thereafter the relocation progression is significantly slower compared to MAAP. A possible reason is the initial fuel distribution where the majority of the fuel in MELCOR (about 75% compared to 36% in MAAP) is distributed in the three innermost rings. Thus, a large amount of core material is formed and transferred to debris upon failure of the CRGT’s. Hypotheses H1 is therefore confirmed. Heat up of the periphery of the core takes time, the outer rings remain intact longer and the relocation progression is predicted to take almost 1.8 times longer in MELCOR. Besides the impact of core nodalization, modeling differences of core support plate failure also affect the duration of the relocation progression. Support plate failure affects all radial rings simultaneously in MAAP compare to MELCOR where each ring fails individually [13]. Moreover, all debris in MAAP is gathered in the lower head for approximately 50 minutes before vessel failure occurs. In MELCOR however, failure is predicted before all debris has accumulated in the bottom of the vessel.

The prediction of hydrogen mass is presented in Figure 20 (total cumulative hydrogen mass) and Figure 21 (cumulative hydrogen mass in containment) and indicates significant difference in modeling of oxidation between the codes. As seen, MELCOR predicts almost twice the amount of hydrogen being generated before core support plate failure compare to MAAP. This can be due to differences in modeling of flow blockages, preventing steam to interact with the fuel assemblies in MAAP to a greater extent than in MELCOR. However, the increase in hydrogen generation obtained at the time of core support plate failure as hot debris interacts with the water pool is predicted similarly between the codes. After vessel failure at 14 500 s and 21 000 s in MAAP and MELCOR respectively, hydrogen is generated as ejected melt interacts with the water present in the cavity. According to Figure 20, the increase is significant in MAAP where almost 50% of the total hydrogen mass is produced instantly after vessel breach. In MELCOR, a less rapid increase is obtained. This phenomenon was not observed in previous comparison where no additional hydrogen was generated in MELCOR at the time of vessel failure [6]. By applying default values for a set of parameters responsible for the heat transfer in the cavity rather than the previously user-specified ones, an increased hydrogen production was obtained. However, the hydrogen level is expected to stabilize which it does not, it keeps increasing even after 40 000 s. Further investigation is needed in order to clarify the behavior.

In MAAP, oxidation of debris particles is only considered during the entrainment and when falling from the lower plenum into the bottom of the cavity [36]. Thus, no oxidation is assumed to take place from the debris bed in lower plenum since the presences of crusts are supposed to disable steam-debris interaction. In contrast, MELCOR calculates oxidation of the unquenched surfaces below the water pool surface. In addition MELCOR simulates continued hydrogen
generation from the peripheral fuel assemblies which remains intact longer compare to MAAP. Subsequently, MELCOR predicts almost twice the amount of hydrogen being generated until the time of vessel breach. Due to the significant difference in modeling and prediction of hydrogen production it is difficult to evaluate the impact of the additional Zircaloy mass (10 %) in MAAP. In MELCOR it is possible to deduce the hydrogen production from oxidation of Zircaloy, steel and B₄C separately, which is not possible in MAAP. Thus, no comparison of the contribution of hydrogen from the different oxidation processes could be made. Hence, hypothesis H4 (see section 3.2) can neither be confirmed nor rejected and further evaluation to determine the impact of the Zircaloy mass is needed.

The collapsed water level in the DC during the first 2000 s after the initiating event agrees well between the codes, as seen in Figure 22. Due to differences in decay heat or elevation of the DC, the DC bottom is reached earlier in MAAP (at 7000 s) compared to MELCOR (around 11 000 s). After 11 000 s the collapsed water level in the lower plenum reaches zero in MELCOR. In MAAP, however, a constant water level of about 1/3 of the initial level remains until vessel breach (at 14 500 s). According to Figure 23, MAAP predicts no water present in the lower plenum after 10 000 s. Hence, the high water level in Figure 22 is inconsistent with the amount of water. The reason behind this inconsistency might derive from a numerical artifact i.e. water mass is very small, basically zero but MAAP still calculates it as if there was some water present on top of the relocated debris, resulting in an incorrect water level.

Furthermore, major differences in water mass in the lower plenum are predicted in MELCOR and MAAP before 6000 s. This might be due to deviations in control volume nodalization. At 6000 s a rapid drop in water mass is obtained in MAAP. This occurs as water is displaced by relocated debris after core support plate failure. Nevertheless, the time of total coolant evaporation is predicted very similarly in MELCOR and MAAP, as seen in Figure 23.

According to Figure 24, MAAP predicts 9-10% higher decay heat compared to MELCOR. In previous comparison the difference was determined to 13 % [6], subsequently the deviation has decreased as a result of the updates made in the MELCOR model. However, the remaining difference is difficult to explain since both codes use the ANS decay heat correlation (tabulated values of decay power with respect to time since scram). The decay power distributions of ²³⁵U, ²³⁸U, ²³⁹Pu are included in the heat calculation, see Equation (1). End-of-cycle values are applied in MAAP compare to the averages over the whole cycle, which are used in MELCOR. However, alterations in the power distribution had insignificant impact on the decay heat (the evaluation is not included in the report).

Differences in prediction of decay heat could arise from discrepancies in the radionuclide inventory. Due to differences in radionuclide grouping, a complete comparison of the nuclides present in the core could not be made. However, some groups in MELCOR are identified with corresponding main contributor in MAAP (nuclides written in parentheses). According to Table 9, MELCOR have smaller initial inventories for all radionuclide groups identified. This is one possible explanation for MAAP’s higher prediction of decay heat compared to MELCOR.
In addition, a warning was obtained in all MELCOR simulations related to the decay heat. Apparently, the decay heat deposited does not equal the calculated available total decay heat. The cause of this message has not been found and further investigation is needed.

Table 9. Normalized initial radionuclide inventory

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>MELCOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nobel gases</td>
<td>0.75</td>
</tr>
<tr>
<td>Alkaline Earths (SrO)</td>
<td>0.76</td>
</tr>
<tr>
<td>Chalcogens (TeO₂)</td>
<td>0.74</td>
</tr>
<tr>
<td>Transition Metals (MoO₂)</td>
<td>0.37</td>
</tr>
<tr>
<td>Tetravalents (CeO₂)</td>
<td>0.34</td>
</tr>
<tr>
<td>Trivalents (La₂O₃)</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Figure 15. Pressure in primary system

Figure 16. Flow rate through SRV’s and ADS
Figure 17. Maximum core temperature (MAAP), maximum fuel temperature (MELCOR)

Figure 18. Debris mass in core region

Figure 19. Debris mass in lower plenum

Figure 20. Total cumulative hydrogen production
Figure 21. Hydrogen mass in containment

Figure 22. Collapsed water level in downcomer (DC) and lower plenum (LP)

Figure 23. Water mass in lower plenum

Figure 24. Decay heat
### 3.3.1 Debris characteristics in lower plenum

According to Figure 26, two types of debris are considered in MAAP i.e. particulate debris bed and continuum pools. The metals and oxides are separated into two different pools, also modeled in MELCOR (section 1.5.2). In addition, MAAP models an oxide embedded crust and five different oxide lower crusts, which are summed up in Figure 26. In MAAP, crust is formed in the vicinity of the vessel wall in lower plenum by debris-to-wall heat transfer. In MELCOR, the conglomerate debris prevents molten material from further relocation by occupying available space for downward relocation and assumes that molten pools cannot penetrate into the particulate debris bed. Hence conglomerated debris has similar characteristics as crusts in MAAP. By comparing the characteristics of the debris predicted by MELCOR and MAAP (Figure 25 respectively Figure 26), significant differences are observed.

Unlike MELCOR, the MAAP simulation estimates a significant fraction of the core liquefying prior to the initial slump to the lower plenum. This can be explained by the fact that in MELCOR simulations, debris formation in upper regions of the core usually results in relocation of particulate debris to the bottom of the core (on top of the core support plate) based on the leveling principle, in contrast, MAAP does not use such leveling principle for particulate debris formed in the upper core region. The relocation of debris into originally open core regions results in debris blockages forming above core plate. This acts as crust preventing further downward relocation. Debris can relocate through these crusts once they fail, which typically requires high temperature conditions [13]. In MAAP, it seems that the amount of molten pools never decreases i.e. molten material never freezes (Figure 26). Contradictory, the presence of crusts increases until 12 000 s. An explanation for this could not be found in the available MAAP data.

Right before vessel breach the mass of the oxide pool is almost half the total amount of debris present in the lower plenum. In contrast, the presence of the molten pools MELCOR varies over time, often no pool is present at all. The same observation was made in EPRI’s report [13]. The amount of oxide pool is significantly less in MELCOR and exists only in the very end before vessel failure. For the major part of the relocation progression, MAAP predicts a constant amount of particulate debris i.e. no mass leaves the region by melting. Transition between the crusts and the continuous oxide pool is only seen at 11 000 s where all debris is accumulated in the lower head before vessel failure. Hence, the transition from particulate debris to distinct molten pools and stratified metal layers are not directly and mechanistically modeled [13]. In MELCOR, properties of the materials are evaluated for each individual cell at each time step. Transition between solid and molten states is therefore calculated continuously and the amount of particulate, conglomerate and continuum pools varies over time. The configuration in MAAP is more stationary and the terminal form of the lower plenum debris is pre-defined compare to MELCOR, which actively calculates the configuration and transitions. This observation is confirmed by EPRI [13].
Figure 25. Lower plenum debris characteristics in MELCOR

Figure 26. Lower plenum debris characteristics in MAAP
According to Figure 27, MELCOR predicts a higher temperature of the metallic pool, especially during the first mass relocation. For the oxide pool (Figure 28) the temperature is higher in MAAP but the temperature profiles are more similar between the codes than for the metallic pool. Since the presences of the molten pools vary over time, the temperatures oscillate accordingly. In contrast to MAAP, MELCOR does not apply a lumped parameter approach to the whole region of the lower plenum. Instead the temperature is calculated independently in each of the 30 cell comprising the lower plenum. Therefore both the average and maximum temperature of the particulate debris is included in Figure 29.
In Figure 30, the material composition of the total debris mass in the lower head is compared. The composition is important due to different thermal conductivity of the compounds having impact on the timing of vessel failure and ex-vessel coolability. The characteristics of the debris i.e. particulate, conglomerate, crusts etc. are not taken into consideration, only the presence of compounds. For example, the amount of ZrO₂ represented in the diagram in MELCOR is the sum of both particulate and conglomerated debris. In MELCOR, the compositions of the oxide and metallic pools could not be specified and are therefore not included. Since the pools contain only a small fraction of the total debris in MELCOR (Figure 25), the pool masses have a minor impact on the results. Pool materials predicted in MAAP are included in the diagram. In MAAP, data is only available at 2, 4 and 6 hours after reactor shut down. A more frequent comparison was therefore not feasible. Fortunately, vessel breach occurs after approximately 4 hours in MAAP. The resulting mass and composition of the debris in the lower head could therefore be compared to MELCOR, where the time of vessel failure occurs after 5.8 hours. After 2 hours, two times more debris has relocated in MELCOR compared to MAAP. The major difference in composition at this time is the quantity of steel, which might corresponds to the collapsed CRGT’s in MELCOR. A good agreement is seen in the resulting debris composition after 4 respective 5.8 hours. Although MAAP has 10 % more initial mass of Zircaloy, MELCOR predicts more ZrO₂ in the resulting debris mass. On the opposite, MAAP predicts a larger fraction of steel oxide compared to the steel mass content. Differences could arise due to different ways of modeling the oxidation processes and flow blockages that prevents steam and debris to interact. After 6 hours, debris is still being ejected to the cavity in MELCOR. At all compared time points, the amount of B₄C debris is almost identical between the codes. A complete compilation of the debris compound composition is available in Appendix B.
3.3.2 Impact of maximum time step size

Occasionally, simulations crashed when parameters were updated in the MELCOR Nordic BWR input. In order to enable complete runs, the maximum time step needed to be decreased. It turned out not to be sufficient just to decrease the time step in the region where the simulation had crashed. Instead the time step had to be altered in the beginning of the simulation to avoid divergence and crash later on. However, alterations turned out to have an impact on the relocation progression, which therefore add uncertainties to the obtained results. To evaluate the influence, a set of simulations were performed with identical input except the maximum time step, $dt_{\text{max}}$. In total seven runs were evaluated with a $dt_{\text{max}}$ between 0.005 and 0.4 applied over the whole problem time except the steady-state run, which was kept identical. These simulations were compared to the ‘MELCOR updated’ run, which had an altering $dt_{\text{max}}$ depending on the problem time according to Appendix C.1. The minimum time step was kept unchanged. All simulations managed to complete the whole problem time except $dt_{\text{max}}$ 0.01, which crashed already after 5000 s (time of core support plate failure). In order to complete the run, $dt_{\text{max}}$ was altered to 0.015 during the first 980 s.

In Table 10, the maximum difference in output obtained due to alterations in time step is presented (over- or underestimation relative to ‘MELCOR updated’). As seen, $dt_{\text{max}}$ has a major impact on the results, especially on the presence of the oxide shell which maximum deviates by $+246\%$. Least sensitive to alteration in time step and also the only underestimation of the result was the resulting debris mass in lower plenum, which maximum deviated by $-8\%$.

Table 10. Maximum deviation in results due to time step

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Maximum deviation from ‘MELCOR updated’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of oxide shell on intact fuel rods (at 10 000 s)</td>
<td>$+246%$</td>
</tr>
<tr>
<td>Time of complete core degradation</td>
<td>$+52%$</td>
</tr>
<tr>
<td>Temperature of intact fuel (at 10 000 s)</td>
<td>$+67%$</td>
</tr>
<tr>
<td>Resulting mass of debris in lower plenum</td>
<td>$-8%$</td>
</tr>
<tr>
<td>Time of vessel failure</td>
<td>$+19%$</td>
</tr>
<tr>
<td>Mass of support plate remained intact</td>
<td>$+29%$</td>
</tr>
<tr>
<td>Mass of hydrogen in containment before vessel breach</td>
<td>$+42%$</td>
</tr>
</tbody>
</table>
According to Figure 31-Figure 36, the range in output is significant and a non-linear trend with respect to the size of $dt_{\text{max}}$ is obtained. However, complete convergence is reached within the core region independently of $dt_{\text{max}}$ until the start of core degradation (around 4300 s) followed by core support failure and debris relocation to lower plenum. Even though no obvious trend is observed, it seems like larger time step ($dt_{\text{max}}$ of 0.3 and 0.4) tend to extend the time required for core degradation. A more massive protective oxide shell on the fuel rods is predicted (Figure 31), which results in the rods remaining intact longer (Figure 32). Thus, the oxidized cladding temperature is a driving factor for fuel rod failure. Although the temperature of the fuel remains higher for larger $dt_{\text{max}}$ during the relocation progression (Figure 33), the temperature level is almost the same at the time of complete degradation i.e. when the last fuel rod has collapsed. Failure of the core support plate is also significantly affected by the time step, as seen in Figure 34. When larger $dt_{\text{max}}$ are applied, more of the plate in the periphery of the core remains intact even after 40 000 s. Subsequently, the resulting debris mass in lower plenum becomes smaller. In addition, the timing of the vessel failure is delayed, according to Figure 35.

The ‘MELCOR updated’ run predicts the most rapid core degradation and most massive first debris mass relocation to lower plenum. In addition, it also predicts the lowest amount of hydrogen before vessel breach, as seen in Figure 36. The only similarity seen with the other simulations performed is the time of vessel failure, which is identical to $dt_{\text{max}}$ 0.2. After 21000 s a $dt_{\text{max}}$ of 0.2 is applied in ‘MELCOR updated’ (see Appendix C.1) and could therefore be a possible explanation.

Reduction of the maximum time step significantly increased the required computation time. With a $dt_{\text{max}}$ of 0.4 the simulation took approximately 6 hours to complete compared to 5 days for the smallest evaluated $dt_{\text{max}}$ of 0.005. The ‘MELCOR updated’ run required about 10 hours. Since no convergence was reached with the time steps evaluated except during the early phase of the accident scenario, further evaluation is necessary to understand the impact of the time step. Additional data from the evaluation of the maximum time step is presented in Appendix C.
Figure 33. Maximum fuel temperature in core with different $dt_{\text{max}}$

Figure 34. Intact core support plate mass with different $dt_{\text{max}}$

Figure 35. Debris mass in lower plenum with different $dt_{\text{max}}$

Figure 36. Hydrogen mass in containment with different $dt_{\text{max}}$
3.4 Parameter studies

In order to analyze the impact of the discrepancies discovered in section 3.1.4 and to evaluate the remaining hypotheses stated in section 3.2, parameter studies were performed in MELCOR. Parameters in Table 7 were altered back to its original value one at the time, keeping the remaining parameters unchanged in the ‘MELCOR updated’ input. The differences in power profiles (Figure 13 and Figure 14) were also evaluated. In addition, a \( dt_{\text{max}} \) of both 0.05 and 0.2 was applied to each parameter study. Thus, both the impact of the parameter alone and the influence together with different time steps could be examined. In order to investigate the impact of the known deviation in decay heat between MELCOR and MAAP, a decay heat multiplier of \( M_{\text{user}} = 1.095 \) (Equation (1)) was applied in MELCOR. Thus, the influence on the in-vessel core degradation and relocation phenomena could be evaluated.

In the seven simulations performed where the decay heat was not amplified (\( M_{\text{user}} = 1 \) in Equation (1)), the decay heat level was insignificantly affected by alterations in the input, as seen in Figure 37. The only increase by 0.8 % was obtained when the irradiation time was increased by a factor of 1.87. Hypothesis H6 (see section 3.2) can therefore be confirmed. Consequently, there must be other factors or models besides the input parameters being alternated that causes the deviation in prediction of decay heat between MELCOR and MAAP.

![Figure 37. Decay heat with alterations in input](image-url)
In Table 11, the results from the parameter studies are presented. The total hydrogen production is compared at the time of vessel failure and normalized to MAAP. Since MAAP predicts a considerably less hydrogen generation before vessel failure compared to MELCOR, the fractions become large. As seen, a delay in timing of complete core degradation and an increase in hydrogen generation compared to ‘MELCOR updated’ (i.e. all parameters updated in accordance to MAAP) were predicted independently of alterations in the input. The only exception is when the original power profiles were applied in combination with a dt\text{max} of 0.2.

Complete core degradation was at most delayed by 1 hour when the failure temperature of the cladding was increased by a factor of 1.17. The results therefore affirms hypothesis H3 (see section 3.2) since the fuel rods remained intact longer when the failure temperature was increased. The failure temperature has no impact on the hydrogen generation (Zircaloy oxidation), which remains unchanged. Thus, the obtained increase in the total amount of hydrogen might be generation due to steel oxidation or from additional oxidation of the remaining fuel assemblies. When a larger debris particle size (i.e. smaller surface area of the total debris available for heat transfer) was applied, the total amount of hydrogen was increased by 18%. Hence, larger particles seem not to result in a smaller amount of hydrogen being produced, which was stated in hypothesis H5 (see section 3.2) and is therefore declined. Other parameters or coupling of parameters must therefore have an impact on the debris/steam interaction.

The results also show that an increase in fuel mass (and initial amount of Zircaloy) by 5%, delays the complete core degradation by almost 1 hour. Since the decay heat is unaffected by the alteration (Figure 37), it takes longer time to heat up and melt the additional core materials. Moreover, an increase in hydrogen mass was obtained in almost all parameter studies, which means that the hydrogen generation is sensitive to parametric alterations.

Furthermore, the impact of the decay heat was evaluated by compensating for the known difference between MELCOR and MAAP. Consequently, both the timing of core support plate failure and vessel failure became more similar to the prediction in MAAP, compare to the other parametric alterations evaluated. Hence, the decay heat has a major impact on the relocation progression. However, vessel breach is still predicted about 76 minutes earlier in MAAP despite similar levels of decay heat. Thus, decay heat is a contributor but cannot alone explain the observed difference in core degradation and relocation progression. Subsequently, there must be other dominant factors of coupling effects or modeling differences contributing to the deviations in results.
Besides the impact of parametric alterations, the maximum time step, $dt_{\text{max}}$, significantly affects the results, as seen in Table 11. Sometimes a combination of a parametric alteration and a certain $dt_{\text{max}}$ was crucial to relocation progression. Most significant example is seen in Appendix D.2, where an increased irradiation time and a $dt_{\text{max}}$ of 0.05 caused significant undesirable divergence compared to when other sizes of $dt_{\text{max}}$ were applied.

Furthermore, data of the debris mass composition in lower plenum before vessel failure is summarized for each parameter study in Appendix D.8. Fractions of steel and UO$_2$ debris to the total amount of debris are insensitive to both parametric alterations and $dt_{\text{max}}$. However, the content of ZrO$_2$ debris is significantly affected. The largest increase from 30 % to 46 % compared to ‘MELCOR updated’ was obtained when the debris falling velocity was decreased.
Table 11. Summarized results from parameter studies; timing of key events and hydrogen generation relative to ‘MELCOR updated’

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MELCOR updated</th>
<th>Support plate failure [s]</th>
<th>Vessel failure [s]</th>
<th>H$_2$ production [normalized]</th>
<th>H$_2$ Zr oxi / total H$_2$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel mass ×1.05</strong></td>
<td>14 950</td>
<td>5127</td>
<td>21 039</td>
<td>1.95</td>
<td>0.65</td>
</tr>
<tr>
<td>$dt_{max}$ 0.05</td>
<td>+3370</td>
<td>-182</td>
<td>+731</td>
<td>2.24</td>
<td>0.69</td>
</tr>
<tr>
<td>$dt_{max}$ 0.2</td>
<td>+3270</td>
<td>-265</td>
<td>+1851</td>
<td>2.69</td>
<td>0.67</td>
</tr>
<tr>
<td><strong>Irr. time ×1.87</strong></td>
<td>+2690</td>
<td>-255</td>
<td>-119</td>
<td>2.35</td>
<td>0.72</td>
</tr>
<tr>
<td>$dt_{max}$ 0.05</td>
<td>+3330</td>
<td>-93</td>
<td>-1949</td>
<td>2.01</td>
<td>0.79</td>
</tr>
<tr>
<td>$dt_{max}$ 0.2</td>
<td>+3400</td>
<td>-51</td>
<td>-549</td>
<td>2.32</td>
<td>0.73</td>
</tr>
<tr>
<td><strong>Particle size ×4.77</strong></td>
<td>+1290</td>
<td>-107</td>
<td>+671</td>
<td>2.29</td>
<td>0.72</td>
</tr>
<tr>
<td>$dt_{max}$ 0.05</td>
<td>+2600</td>
<td>-218</td>
<td>-1509</td>
<td>2.22</td>
<td>0.70</td>
</tr>
<tr>
<td>$dt_{max}$ 0.2</td>
<td>+2600</td>
<td>-88</td>
<td>+2421</td>
<td>2.08</td>
<td>0.75</td>
</tr>
<tr>
<td><strong>Cladding fail temp ×1.17</strong></td>
<td>+3760</td>
<td>-135</td>
<td>+151</td>
<td>2.49</td>
<td>0.65</td>
</tr>
<tr>
<td>$dt_{max}$ 0.05</td>
<td>+2510</td>
<td>-343</td>
<td>+231</td>
<td>2.19</td>
<td>0.71</td>
</tr>
<tr>
<td>$dt_{max}$ 0.2</td>
<td>+3210</td>
<td>-205</td>
<td>+631</td>
<td>2.09</td>
<td>0.76</td>
</tr>
<tr>
<td><strong>Velocity ×0.02</strong></td>
<td>+1520</td>
<td>93</td>
<td>+1341</td>
<td>2.50</td>
<td>0.71</td>
</tr>
<tr>
<td>$dt_{max}$ 0.05</td>
<td>+860</td>
<td>64</td>
<td>+1661</td>
<td>2.48</td>
<td>0.69</td>
</tr>
<tr>
<td>$dt_{max}$ 0.2</td>
<td>+2860</td>
<td>-30</td>
<td>+2031</td>
<td>2.67</td>
<td>0.64</td>
</tr>
<tr>
<td><strong>Power profiles</strong></td>
<td>+1790</td>
<td>-116</td>
<td>-9</td>
<td>2.42</td>
<td>0.67</td>
</tr>
<tr>
<td>$dt_{max}$ 0.05</td>
<td>+2220</td>
<td>-208</td>
<td>+1481</td>
<td>2.29</td>
<td>0.71</td>
</tr>
<tr>
<td>$dt_{max}$ 0.2</td>
<td>-700</td>
<td>1</td>
<td>-209</td>
<td>1.90</td>
<td>0.85</td>
</tr>
<tr>
<td><strong>Decay heat ×1.095</strong></td>
<td>+210</td>
<td>-462</td>
<td>-1979</td>
<td>2.34</td>
<td>0.69</td>
</tr>
<tr>
<td>$dt_{max}$ 0.05</td>
<td>+2450</td>
<td>-395</td>
<td>+681</td>
<td>2.23</td>
<td>0.73</td>
</tr>
<tr>
<td>$dt_{max}$ 0.2</td>
<td>+2590</td>
<td>-572</td>
<td>-1 669</td>
<td>2.19</td>
<td>0.74</td>
</tr>
<tr>
<td><strong>MAAP</strong></td>
<td>-3000</td>
<td>-636</td>
<td>-6541</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

- 54 -
In the majority of the parameter studies, a delay in completed core degradation (i.e. all fuel rods have failed) was obtained compare to ‘MELCOR updated’. However, the timing of core support plate failure was insignificantly affect by alterations in input, deviation within a few minutes was obtained.

In Table 12, the timing between complete core degradation and vessel failure is presented. Alteration in cladding failure temperature had the most impact and the time difference was reduced by a factor of 2.5 compare to ‘MELCOR updated’. Besides the cladding failure temperature, alterations in irradiation time and fuel mass seem to have a larger impact on reducing the time difference than an amplified decay heat.

Table 12. Timing between completed core degradation and vessel failure

<table>
<thead>
<tr>
<th></th>
<th>Time between complete degradation and vessel failure [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MELCOR updated</td>
<td>6089</td>
</tr>
<tr>
<td>Fuel mass ×1.17</td>
<td>3450</td>
</tr>
<tr>
<td>Irr. time ×1.87</td>
<td>3280</td>
</tr>
<tr>
<td>Particle size ×4.77</td>
<td>5470</td>
</tr>
<tr>
<td>Fail temp ×1.17</td>
<td>2480</td>
</tr>
<tr>
<td>Velocity ×0.02</td>
<td>5900</td>
</tr>
<tr>
<td>Power profiles</td>
<td>4290</td>
</tr>
<tr>
<td>Decay heat ×1.095</td>
<td>3900</td>
</tr>
<tr>
<td>MAAP</td>
<td>2548</td>
</tr>
</tbody>
</table>

Additional data from the parameter studies is presented in Appendix D.
3.5 Evaluation of hypotheses

Through the performed simulations and analysis of the results, the hypotheses stated in section 3.2 have been evaluated and discussed. In Table 13, the outcome of hypothesis H1-H6 is summarized and the status is stated whether the premises could be confirmed, declined or undecided by the study.

Differences in core nodalization in combination with the failure modeling applied in MELCOR were confirmed to have an impact of the debris mass relocation to lower plenum (H1). A more massive first relocation to lower plenum is obtained in MELCOR since the initial fuel distribution is much more centered in the core compared to MAAP. However, no alteration in nodalization was performed in MELCOR to confirm the statement further.

Core support plate failure occurred earlier (12 min) in MELCOR compared to MAAP. The opposite was stated in hypothesis H2. The hypothesis was based on the amount of steel mass comprising the support plate that consequently should be able to remain intact longer. However, the debris mass in core region was predicted significantly larger in MELCOR and may have resulted in a heavier load on the plate, causing it to collapse earlier. Possibly, the interpretation of the steel node content in MAAP data was incorrect. Thus, no conclusion could be drawn whether interpretation (a) or (b) of the nodalization in MAAP is more correct than another, but hypothesis H2 was declined. Simulations performed in MELCOR with alteration in support plate thickness are needed in order to evaluate the impact on the relocation progression.

Hypothesis H3 was confirmed since an increase in cladding failure temperature (by a factor of 1.17 in the parameter study) had a significant impact on the timing of fuel rod collapse and delayed complete core degradation by 20%. Fuel rod collapse is still predicted 3000 s earlier in MAAP compared to MELCOR even though the same cladding failure temperature was applied. Hence, modeling differences or other factors have an impact on core degradation besides the cladding failure temperature. Due to the significant differences in modeling of oxidation and flow blockages [13], the impact of the additional Zircaloy mass (10%) applied in MAAP could not be evaluated properly. Hence, hypothesis H4 remains undecided. However, the hydrogen production is sensitive to alterations in input and an increase was obtained in almost all parameter studies.

Contradictory to the statement in H5, larger particle size (i.e. smaller surface-area-to-volume ratio) did not result in less hydrogen being generated. Further investigation is needed in order to determine if there are other parameters or coupling effects that affect the results or modeling options e.g. Zircaloy oxidation cut off fraction.

Although a difference in decay heat prediction by 9-10% remains unexplained, it was confirmed that the only input parameter altered in MELCOR with an impact on the decay heat was the irradiation time (H6). However, the impact was not significant and an increase by 0.8% was obtained when the irradiation time was increased by a factor of 1.87.
Table 13. Summarized result of stated hypotheses

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Observable factor</th>
<th>Status</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H1.</strong> More massive first relocation to lower plenum because of nodalization (fuel distribution) and failure modeling</td>
<td>Debris mass in lower plenum</td>
<td>Confirmed</td>
<td>Alterations in nodalization could confirm hypothesis further</td>
</tr>
<tr>
<td><strong>H2.</strong> Later relocation to lower plenum because of a higher steel content of the core support plate</td>
<td>Time of mass relocation to lower plenum</td>
<td>Declined</td>
<td>Alteration in plate thickness could confirm hypothesis further</td>
</tr>
<tr>
<td><strong>H3.</strong> Later fuel rod collapse due to higher cladding failing temperature</td>
<td>Intact UO₂</td>
<td>Confirmed</td>
<td>Almost proportional delay of collapse with respect to temperature increase</td>
</tr>
<tr>
<td><strong>H4.</strong> Less hydrogen generation because of less initial Zircaloy mass (10 %)</td>
<td>Hydrogen generation</td>
<td>Undecided</td>
<td>Significant differences in oxidation modeling, hard to evaluate H4</td>
</tr>
<tr>
<td><strong>H5.</strong> Less hydrogen generation due to larger particle size of the particulate debris (smaller surface-area-to-volume ratio)</td>
<td>Hydrogen generation</td>
<td>Declined</td>
<td>Other factors than particle size have to be dominant</td>
</tr>
<tr>
<td><strong>H6.</strong> Similar level of decay heat independently of alterations in input (except irradiation time) due to ANS decay heat calculation in Equation (1)</td>
<td>Decay heat</td>
<td>Confirmed</td>
<td>Other factors must contribute to the difference in decay heat</td>
</tr>
</tbody>
</table>
3.6 Other improvements of MELCOR model

In the meantime of the code comparison, some discrepancies were found and updated without any further evaluation. Improvements made in the MELCOR input deck are listed below:

- Initiation of scram occurs at 0 s after loss of power in accordance to MAAP (previously a value of 10 s delay was applied).
- The steady-state power level before initiation of scram differs from the specified operational power of 3900 MW both in MELCOR (3922 MW) and MAAP (3882 MW). Subsequently different initial levels of decay power were obtained. By readjusting the user-specified decay heat contribution from original 5.87 % to 6.9 %, a steady-state power in accordance to MAAP was obtained. If a power output of 3900 MW is desired, the decay heat contribution should be adjusted to 6.44 %.
- Porosity of the particulate debris was increased from 25 % to 40 %, a value more coincide with experimental data [23].
- Updated logics for ADS and ECCS
- Hygroscopic model activated

4 Summary of main results

Below, the main results from the study are summarized:

- The core nodalization and subsequently initial fuel distribution differ significantly between MELCOR and MAAP input decks. This possibly explains differences in prediction of debris relocation progression.
- Difference in prediction of decay heat was decreased from initial 13 % to 9-10 %. Why MAAP still predicts a higher level of decay heat even though both codes apply ANS calculations needs to be clarified. Since the parameter study showed that the decay heat is insensitive to alterations in input, the reduced deviation in predicted decay heat must arise from other changes made in the model.
- Vessel failure is predicted earlier in MAAP (4.0 h) compared to MELCOR (5.8 h). However, the difference in prediction between MECLOR and MAAP has been reduced by 1.2 h compared to the results obtained in the previous comparison [6]. Thus, the reduction of uncertainty due to differences in code input has together with other updates in MELCOR input successfully made the codes to predict more similar results.
- When a decay heat multiplier was applied in MELCOR to compensate for the known difference in decay heat, the difference in timing of vessel failure was reduced even
further (vessel failure predicted after 5.3 h in MELCOR). Hence, the decay heat is an important factor but it cannot alone explain the remaining differences in prediction of core degradation and relocation phenomena. Subsequently, there must be other dominant factors e.g. nodalization, code models or coupling effects contributing to deviations in results.

- Differences in oxidation models and flow blockage explain the different estimates of hydrogen generation in each code. However, a hydrogen increase as debris is ejected into the water-filled cavity was obtained in MELCOR, which had not been seen in previous comparisons [5], [6]. Hence, the obtained result has become more similar to the prediction MAAP.

- Representation of the debris characteristics in lower plenum differ significantly between the codes. MAAP applies a pre-defined terminal form of the configuration while MELCOR calculates the debris formation and the transitions in each cell individually. Most significant is the difference in prediction of the presence of metallic and oxide pools.

- Good agreement of the material composition of the resulting debris mass in lower plenum is observed between MELCOR and MAAP. Minor differences in oxides are most likely due to the modeling differences (flow blockages) applied in the codes.

- The choice of time step has a significant impact on the late phase of the core degradation and relocation progression. A non-linear convergence with respect to the size of time step was obtained. However, convergence is reached within the core region i.e. the early phase of core degradation is insensitive to alteration in $dt_{max}$. 
5 Conclusions

This study of the in-vessel accident progression was carried out for Nordic BWR’s by comparing the results obtained in SBO simulations with two different severe accident computer codes; MELCOR and MAAP. In the comparison performed, several discrepancies in the MELCOR Nordic BWR input decks and available MAAP data were discovered, which had not been taken into consideration in previous comparisons. By identifying and eliminating discrepancies in input, a reduction of uncertainty due to in code input was obtained. Thus, differences in modeling between the codes could be addressed.

The major outcome of the study is presented below:

- Successfully identification of discrepancies and reduced uncertainty arisen from differences in code input. Thus, the MELCOR input was updated and is numerically more similar to MAAP data. However, no alterations in core nodalization were performed.
- The time step was identified as a major source of uncertainty in the MELCOR results. Alterations in the maximum time step, $dt_{\text{max}}$, have a significant impact during the late phase of the core degradation progression. Numerical convergence is not provided in the MELCOR code, nevertheless, convergence is necessary for future investigation of modeling effects.
- Improved understanding of uncertainties and code limitations in MELCOR and MAAP.
- Increased knowledge about in-vessel core degradation and relocation phenomena, timing of key events and representation of the resulting properties of the debris bed in the vessel lower plenum of Nordic BWR’s. This is valuable information for the ex-vessel accident progression and development of SAM strategies.
- Despite significant differences in modeling, end-of-transient-values (e.g. hydrogen generation and debris mass composition) are predicted similarly between MELCOR and MAAP.
- Due to several unresolved issues regarding failure modeling, oxidation modeling and decay heat calculation further comparisons are necessary in order to fully understand the differences in severe accident modeling and to identify strengths and weaknesses within each code.
- With further development and increased knowledge, MELCOR has the possibility to become more valuable in decision-making regarding severe accident analysis and subsequently complement MAAP, which currently is the only official software tool for this application in Sweden.
5.1 Recommendations for further work

In order to gain more knowledge about differences in modeling between MELCOR and MAAP and to understand deviations in results, further investigation is necessary. If more information about MAAP were available e.g. complete input decks, manuals with modeling options and calculations applied, a more comprehensive comparison could be performed and the obtained results explained better.

Some recommendations regarding further development of the MELCOR Nordic BWR model and comparison of the results to MAAP are listed below:

- Compensation for the missing mass of Zircaloy (10%) comprising the water channel structure of the fuel assembly that is taken into consideration in MAAP. Since no specific input parameter exist for this purpose in MELCOR the additional mass needs to be implemented in a proper way.

- Redistribution of the core nodalization in accordance to MAAP. A finer axial nodalization of the active core (10 levels instead of 6) and radial ring division where the initial fuel mass distribution is increasing towards the outer rings might have a significantly impact on the relocation progression.

- Further investigation of the decay heat calculations in order to understand why a lower level of the decay heat (9-10 %) is predicted in MELCOR compared to MAAP. The impact of the initial radionuclide mass inventory and its distribution within the active core should be evaluated and the connection to core power distribution analyzed.

- Study the increase in hydrogen generation obtained when debris is entering the lower plenum in MELCOR. Heat transfer coefficients in the cavity should be investigated. In addition, the High Pressure Melt Ejection model (HPME) should be implemented which considers oxidation of metallic elements in the ejected debris that the currently applied Low Pressure Melt Ejection model (LPME) model does not.

- Further evaluation of the impact of the maximum time step in order to reach convergence also after start of mass relocation and subsequently reduce the uncertainty in results arisen from the choice of $dt_{max}$. A balance between the size of $dt_{max}$ and required computational time should be taken into consideration. The $dt_{max}$ should only be reduced in time regions where it is necessary, but remained larger elsewhere to keep the computational time reasonably short.

- Application of state-of-the-art sensitivity – uncertainty quantification methods.

- Perform comparison with the most recent code versions, MELCOR 2.1 and MAAP5.
6 Bibliography


34. **Nilsson, L.** *Development of an Input Model to MELCOR 1.8.5 for Oskarshamn 3 BWR.* Nyköping: Statens Kärnkraftsinspektion (SKI), 2006.


Appendix A. Scenarios available for comparison

In the following section MELCOR cases A-C are identified with corresponding scenarios available in MAAP including an overview of the safety systems functionality. All cases are transients with SBO as initiating event if nothing else is specified. The thicker line in the tables separates systems taken into consideration in PSA level 1 (core damage) from PSA level 2 (plant damage).

yes: system is successfully initiated / rupture disk bursts
no: system failed to initiate / rupture disk kept intact
-: system is not included in the sequence

A.1. Overview HS2-TH1 scenarios (Case A in MELCOR)

Table 14. Overview HS2-TH1 scenarios

<table>
<thead>
<tr>
<th>System</th>
<th>MAAP case</th>
<th>7c</th>
<th>26</th>
</tr>
</thead>
<tbody>
<tr>
<td>354- Scram</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>314TA- SRV</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>327- AFW</td>
<td>no</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>314TB- ADS</td>
<td>no</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>358- DW flooding</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>361- CVS via atmosphere</td>
<td>no</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>322- CHRs spray + cooling</td>
<td>no</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>322- CHRs cooling</td>
<td>no</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>322O- CHRs (fire water)</td>
<td>no</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>322O- CHRs regulation</td>
<td>-</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>362- CVS MVSS</td>
<td>no</td>
<td>yes*</td>
<td></td>
</tr>
</tbody>
</table>

* Manually opened after 10 h
### A.2. Overview HS2-TL4 scenarios (Case B in MELCOR)

Table 15. Overview HS2-TL4 scenarios

<table>
<thead>
<tr>
<th>System</th>
<th>MAAP case</th>
<th>5b</th>
<th>5c</th>
<th>6</th>
<th>7</th>
<th>12b</th>
<th>13b</th>
<th>27</th>
</tr>
</thead>
<tbody>
<tr>
<td>354- Scram</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>314TA- SRV</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>327- AFW</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>314TB- ADS</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>323- ECCS</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>358- DW flooding</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>361- CVS via atmosphere</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>322- CHRs spray + cooling</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>no</td>
</tr>
<tr>
<td>322- CHRs spray</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>yes</td>
<td>no</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>322- CHRs cooling</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>no</td>
</tr>
<tr>
<td>322O- CHRs (fire water)</td>
<td>-</td>
<td>-</td>
<td>no</td>
<td>no</td>
<td>-</td>
<td>-</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>322O- CHRs regulation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>no</td>
</tr>
<tr>
<td>362- CVS MVSS</td>
<td>-</td>
<td>-</td>
<td>yes</td>
<td>no</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>no</td>
</tr>
</tbody>
</table>
A.3. Overview HS3-SL1 scenario (Case C in MELCOR)

The sequence HS3-SL1 is not simulated in MAAP. However, HS3-SL2 is identical except initiating event is LOCA instead of SBO.

Table 16. Overview HS3-SL2 scenario

<table>
<thead>
<tr>
<th>System</th>
<th>MAAP case</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>354- Scram</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>314TA- SRV</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>327- AFW</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>314TB- ADS</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>323- ECCS</td>
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<td></td>
</tr>
<tr>
<td>321- RHRS</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>358- DW flooding</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>361- CVS via atmosphere</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>322- CHRs spray</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>322- CHRs cooling</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>322O- CHRs (fire water)</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>362- CVS MVSS</td>
<td>no</td>
<td></td>
</tr>
</tbody>
</table>
Appendix B. MAAP data
Appendix C.  Additional data

This appendix contains additional data from the simulations performed in MELCOR.

C.1. Time step used in ‘MELCOR updated’ simulation

Table 17. Time step applied in ‘MELCOR updated’

<table>
<thead>
<tr>
<th>Problem time [s]</th>
<th>$dt_{\text{max}}$</th>
<th>$dt_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-300</td>
<td>0.1</td>
<td>1.0e-4</td>
</tr>
<tr>
<td>0</td>
<td>0.01</td>
<td>1.0e-4</td>
</tr>
<tr>
<td>20</td>
<td>0.1</td>
<td>1.0e-4</td>
</tr>
<tr>
<td>1000</td>
<td>0.05</td>
<td>1.0e-4</td>
</tr>
<tr>
<td>3000</td>
<td>0.05</td>
<td>1.0e-4</td>
</tr>
<tr>
<td>5000</td>
<td>0.05</td>
<td>1.0e-7</td>
</tr>
<tr>
<td>7000</td>
<td>0.05</td>
<td>1.0e-6</td>
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<td>1.0e-6</td>
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<tr>
<td>11000</td>
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<td>1.0e-6</td>
</tr>
<tr>
<td>13000</td>
<td>0.05</td>
<td>1.0e-6</td>
</tr>
<tr>
<td>17000</td>
<td>0.1</td>
<td>1.0e-6</td>
</tr>
<tr>
<td>19000</td>
<td>0.1</td>
<td>1.0e-7</td>
</tr>
<tr>
<td>21000</td>
<td>0.2</td>
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<td>1.0e-6</td>
</tr>
<tr>
<td>35000</td>
<td>0.5</td>
<td>1.0e-6</td>
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</tbody>
</table>
C.2. Evaluation of maximum time step

Figure 38. In-vessel hydrogen production with different \( dt_{\text{max}} \)

Figure 39. Hydrogen production Zr oxidation with different \( dt_{\text{max}} \)

Figure 40. Hydrogen production steel oxidation with different \( dt_{\text{max}} \)

Figure 41. Hydrogen production B\(_4\)C oxidation with different \( dt_{\text{max}} \)
Figure 42. Particulate debris in lower plenum with different $dt_{\text{max}}$

Figure 43. Conglomerated debris in lower plenum with different $dt_{\text{max}}$

Figure 44. Fraction Zr to total debris with different $dt_{\text{max}}$

Figure 45. Fraction $\text{ZrO}_2$ to total Zr debris with different $dt_{\text{max}}$
Figure 46. Fraction steel to total debris with different $dt_{max}$

Figure 47. Fraction steel oxides to steel debris with different $dt_{max}$

Figure 48. Fraction UO$_2$ to total debris with different $dt_{max}$

Figure 49. Fraction metal to total debris with different $dt_{max}$
Appendix D. Parameter studies

In this appendix additional results from the parameter studies are presented. In addition to the parametric alteration, the impact of the maximum time step, $dt_{max}$, is evaluated. In ‘MELCOR updated’ all input parameters are updated in accordance to MAAP.

D.1. Initial UO\textsubscript{2} mass

![Graph of Debris mass in lower plenum with fuel mass $\times 1.05$]

Figure 50. Debris mass in lower plenum with fuel mass $\times 1.05$

![Graph of Hydrogen mass in containment with fuel mass $\times 1.05$]

Figure 51. Hydrogen mass in containment with fuel mass $\times 1.05$

![Graph of Fraction Zr to total debris with fuel mass $\times 1.05$]

Figure 52. Fraction Zr to total debris with fuel mass $\times 1.05$

![Graph of Fraction ZrO\textsubscript{2} to Zr debris with fuel mass $\times 1.05$]

Figure 53. Fraction ZrO\textsubscript{2} to Zr debris with fuel mass $\times 1.05$
Figure 54. Fraction steel to total debris with fuel mass $\times 1.05$

Figure 55. Fraction steel oxides to steel with fuel mass $\times 1.05$

Figure 56. Fraction UO2 to total debris with fuel mass $\times 1.05$

Figure 57. Fraction metal to total debris with fuel mass $\times 1.05$
D.2. Irradiation time

Figure 58. Debris mass in lower plenum with irradiation time ×1.87

Figure 59. Hydrogen mass in containment with irradiation time ×1.87

Figure 60. Fraction Zr to total debris with irradiation time ×1.87

Figure 61. Fraction ZrO₂ to Zr debris with irradiation time ×1.87
Figure 62. Fraction steel to total debris with irradiation time ×1.87

Figure 63. Fraction steel oxides to steel debris with irradiation time ×1.87

Figure 64. Fraction UO2 to total debris with irradiation time ×1.87

Figure 65. Fraction metal to total debris with irradiation time ×1.87
D.3. Particle size of particulate debris in lower plenum

Figure 66. Debris mass in lower plenum with particle size $\times 4.77$

Figure 67. Hydrogen mass in containment with particle size $\times 4.77$

Figure 68. Fraction Zr to total debris with particle size $\times 4.77$

Figure 69. Fraction ZrO$_2$ to Zr debris with particle size $\times 4.77$
Figure 70. Fraction steel to total debris with particle size ×4.77

Figure 71. Fraction ZrO$_2$ to steel debris with particle size ×4.77

Figure 72. Fraction UO$_2$ to total debris with particle size ×4.77

Figure 73. Fraction metal to total debris with particle size ×4.77
D.4. Cladding failure temperature

Figure 74. Debris mass in lower plenum with cladding failure temperature ×1.17

Figure 75. Hydrogen in containment with cladding failure temperature ×1.17

Figure 76. Fraction Zr to total debris with cladding failure temperature ×1.17

Figure 77. Fraction ZrO₂ to Zr debris with cladding failure temperature ×1.17
Figure 78. Fraction steel to total debris with cladding failure temperature ×1.17

Figure 79. Fraction steel oxides to steel debris with cladding failure temperature ×1.17

Figure 80. Fraction UO$_2$ to total debris with cladding failure temperature ×1.17

Figure 81. Fraction metal to total debris with cladding failure temperature ×1.17
D.5. Debris falling velocity

Figure 82. Debris mass in lower plenum with debris falling velocity ×0.02

Figure 83. Hydrogen mass in containment with debris falling velocity ×0.02

Figure 84. Fraction Zr to total debris with debris falling velocity ×0.02

Figure 85. Fraction ZrO₂ to Zr debris with debris falling velocity ×0.02
Figure 86. Fraction steel to total debris with debris falling velocity ×0.02

Figure 87. Fraction steel oxides to steel debris with debris falling velocity ×0.02

Figure 88. Fraction UO$_2$ to total debris with debris falling velocity ×0.02

Figure 89. Fraction metal to total debris with debris falling velocity ×0.02
D.6. Power profiles

Figure 90. Debris mass to lower plenum with power profiles in accordance to MAAP

Figure 91. Hydrogen mass in containment with power profiles in accordance to MAAP

Figure 92. Fraction Zr to total debris with power profiles in accordance to MAAP

Figure 93. Fraction ZrO2 to Zr debris with power profiles in accordance to MAAP
Figure 94. Fraction steel to total debris with power profiles in accordance to MAAP

Figure 95. Fraction steel oxides to steel debris with power profiles in accordance to MAAP

Figure 96. Fraction UO₂ to total debris with power profiles in accordance to MAAP

Figure 97. Fraction metal to total debris with power profiles in accordance to MAAP
D.7. Decay heat

Figure 98. Debris mass in lower plenum with decay heat $\times 1.095$

Figure 99. Hydrogen in containment in lower plenum with decay heat $\times 1.095$

Figure 100. Fraction Zr to total debris with decay heat $\times 1.095$

Figure 101. Fraction ZrO$_2$ to Zr debris with decay heat $\times 1.095$
Figure 102. Fraction steel to total debris with decay heat ×1.095

Figure 103. Fraction steel oxides to steel debris with decay heat ×1.095

Figure 104. Fraction UO₂ to total debris with decay heat ×1.095

Figure 105. Fraction UO₂ to total debris with decay heat ×1.095
D.8. Impact on resulting debris mass in lower plenum

Table 18. Summarized results from parameter studies; debris mass in lower plenum (normalized)

<table>
<thead>
<tr>
<th>MELCOR updated</th>
<th>Zr to tot debris [-]</th>
<th>ZrO₂ to Zr debris [-]</th>
<th>Steel to tot debris [-]</th>
<th>UO₂ to tot debris [-]</th>
<th>Steel oxides to steel debris [-]</th>
<th>Tot metal to tot debris [-]</th>
</tr>
</thead>
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<tr>
<td>Fuel mass ×1.05</td>
<td>0.14</td>
<td>0.30</td>
<td>0.31</td>
<td>0.48</td>
<td>0.08</td>
<td>0.45</td>
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<tr>
<td>dt max 0.05</td>
<td>0.13</td>
<td>0.39</td>
<td>0.30</td>
<td>0.49</td>
<td>0.08</td>
<td>0.43</td>
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<td>dt max 0.2</td>
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<td>0.45</td>
<td>0.30</td>
<td>0.49</td>
<td>0.10</td>
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<tr>
<td>Irr. time ×1.87</td>
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<td>0.31</td>
<td>0.48</td>
<td>0.07</td>
<td>0.44</td>
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<td>0.32</td>
<td>0.33</td>
<td>0.47</td>
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<td>0.46</td>
</tr>
<tr>
<td>dt max 0.2</td>
<td>0.13</td>
<td>0.43</td>
<td>0.31</td>
<td>0.48</td>
<td>0.07</td>
<td>0.44</td>
</tr>
<tr>
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<td>0.31</td>
<td>0.48</td>
<td>0.07</td>
<td>0.44</td>
</tr>
<tr>
<td>dt max 0.05</td>
<td>0.13</td>
<td>0.39</td>
<td>0.31</td>
<td>0.48</td>
<td>0.08</td>
<td>0.44</td>
</tr>
<tr>
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<td>0.38</td>
<td>0.31</td>
<td>0.48</td>
<td>0.06</td>
<td>0.44</td>
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<tr>
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<td>0.48</td>
<td>0.10</td>
<td>0.44</td>
</tr>
<tr>
<td>dt max 0.05</td>
<td>0.13</td>
<td>0.38</td>
<td>0.31</td>
<td>0.48</td>
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<td>0.44</td>
</tr>
<tr>
<td>dt max 0.2</td>
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<td>0.32</td>
<td>0.48</td>
<td>0.05</td>
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<td>dt max 0.2</td>
<td>0.14</td>
<td>0.34</td>
<td>0.31</td>
<td>0.48</td>
<td>0.06</td>
<td>0.45</td>
</tr>
<tr>
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<td>0.31</td>
<td>0.48</td>
<td>0.08</td>
<td>0.43</td>
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<tr>
<td>dt max 0.05</td>
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<td>0.31</td>
<td>0.48</td>
<td>0.07</td>
<td>0.44</td>
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<tr>
<td>dt max 0.2</td>
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<td>0.33</td>
<td>0.48</td>
<td>0.07</td>
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