Total loss of AC power analysis for EPR reactor

Piotr Darnowski a, *, Eleonora Skrzypek a, b, Piotr Mazgaj a, Konrad Świrski a, Pascal Gandrille c

a Warsaw University of Technology, Institute of Heat Engineering, Nowowiejska 21/25, 00-665 Warsaw, Poland
b National Centre for Nuclear Research (NCBJ), A. Soltana 7, 05-400 Otwock-Świerk, Poland
c AREVA NP SAS, Tour AREVA, 1 place Jean Millier, 92084 Paris La Défense, France

HIGHLIGHTS

• Total loss of AC power (Station Blackout) was simulated for the EPR reactor model.
• In-vessel phase of the accident is under consideration.
• Comparison of MELCOR and MAAP results is presented.
• MELCOR and MAAP results are comparable.

ARTICLE INFO

Article history:
Received 25 April 2014
Received in revised form 27 March 2015
Accepted 28 March 2015

ABSTRACT

In this paper the results of severe accident simulations for the EPR reactor in the case of loss of offsite power combined with total failure of all diesel generators (total loss of AC power) are presented. Calculations were performed with MELCOR 2.1 computer code for in-vessel phase of the accident. In this scenario, the unavailability of all offsite and onsite power sources and the lack of cooling leads directly to core degradation, material relocation to the lower plenum and rupture of the reactor pressure vessel. MELCOR results were compared qualitatively and quantitatively with MAAP4 code results and show a good agreement.

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1. Introduction

In this work the results of the total loss of AC power (Total Station Blackout) scenario simulations for the EPR reactor are presented. This accident is a Severe Accident (SA) being the simultaneous combination of Loss of Offsite Power (LOOP) with unavailability of all diesel generators, both four Emergency Diesel Generators (EDG) and two Ultimate Diesel Generators (UDG or SBO diesels) [ONR, 2013].

To provide the reader with full understanding of the analyzed accident and of the differences between the terminology for EPR reactor designs, the following explanation of the scenarios characteristics is presented. In common terminology, total loss of AC power is equivalent to Station Blackout (SBO) accident. Precisely, in the EPR case SBO has a somewhat different meaning. Station Blackout event consists of LOOP and failure of all four EDGs leading to the total loss of power on the emergency and non-emergency 10 kV busbars (Areva and EDF, 2013b; NRC, 1988). In order to withstand such conditions, EPR is equipped with two UDG diesel generators, classified as alternate alternating current (AAC) sources, dedicated to SBO. Low power UDGs are connected to 690 V busbars of two safety trains. They are fully diversified, redundant, protected and physically separated with 24 h autonomy each, in the case of basic design (ONR, 2013). During SBO event, UDGs mainly provide power to two emergency feedwater pumps, part of ventilation system, crucial I&C and Main Control Room. There are also provisions to provide power to other systems. In principle, one UDG is able to cope with SBO and in these circumstances, it does not lead directly to the core melt sequence (Areva and EDF, 2013b; ONR, 2013). On the contrary, total loss of AC power includes SBO and unavailability of two UDG generators and it is a severe accident. It leads to core degradation with the violation of the reactor pressure vessel (RPV) integrity in a couple of hours (ONR, 2013). The distinction between these two accidents is important from the point of response to the system behavior. This response is directed by the operator action during the course of accident progression.
The reactor design of EPR has its own Emergency Operating Procedures (EOP) and Operating Strategies for Severe Accidents (OSA), which defines operators’ actions during Design Basis Accidents and Severe Accidents (Prior and Sauvage, 2006). During total loss of AC power reactor enters into OSA regime and for SBO it does not. The transition between those two operational regimes is determined by the core exit threshold temperature value of 650 °C. The principles of the accident management assembled in the EOPs and OSA guidelines describe the need of the system depressurization to avoid the High Pressure Melt Ejection (HPME) from the RPV. The HPME can lead to strong molten corium interaction with cavity materials and could lead to early containment failure by Direct Containment Heating (DCH) (Fischer et al., 2014; Areva and EDF, 2013c; Sehgal, 2012; Bouteille et al., 2006; Fischer, 2004). Depressurization core exit temperature trigger is consistent with Westinghouse Owners Group Severe Accident Management Guidelines (SAMG) (Sehgal, 2012). The temperature criterion for depressurization activation was selected to prevent accumulator water injection after the onset of core melt and in consequence, to avoid high temperature core reflooding with strong oxidation (Areva and EDF, 2013c). For the EPR, accident management aims to depressurize RCS and the main recovery action is the SG depressurisation, being an action performed in the framework of EOPs. For the cases in which the SG depressurization is not successful, the action to be undertaken by the operator in the frames of EOPs, is the primary Feed and Bleed procedure performed by PDS actuation (first level of PDS) (Areva and EDF, 2013c). The Feed & Bleed procedure involves the Safety Injection System water make-up, while for the total loss of AC power water supply is provided only by the passive accumulators. For the mitigation of the consequences of the severe accident, operator is opening the PDS system and it is part of OSA framework (second level of PDS actuation, if not yet opened) (Areva and EDF, 2013c). Total loss of AC power analysis presented in this paper assumes that there is no SG depressurization, primary Feed and Bleed is not possible and PDS are not activated until the entrance to the severe accident operation regime. This scenario is believed to be the most severe to PDS valves design due to rapid high energy steam discharge.

Despite of all, total loss of AC power and severe accidents for EPR, in general, are characterized by very low probability. In the framework of Probabilistic Safety Assessment (PSA) studies for EPR reactor, core damage sequences initiated by loss of offsite power are the dominant contributor to the overall Core Damage Frequency (CDF). Among those events the loss of all diesels is an important cut-set and total CDF for Short Term and Long Term LOOP type initiating events equals about 1.3 × 10⁻⁶ [1/year] (Julin et al., 2014).

From the very beginning the concept of severe accident mitigation was present as a part of design process of EPR reactor (Czech et al., 1999). The reactor is characterized by robust design based on the proven defense in-depth concepts. It has high level of redundancy, diversity as well as a group of passive and active features developed to mitigate severe accidents, minimize any releases and to protect the Public from any potential radiological effects (Fischer et al., 2014; Bouteille et al., 2006; Fischer, 2004).

The Fukushima-Daichi NPP accident with long term Station Blackout was caused by extreme external events and vulnerabilities in the plant design. It forced plant operators and designers of all nuclear reactors to review their designs and improve them and it is also the case for EPR. The series of meltdowns reminded the whole Nuclear Community of the importance of the SBO type events and the key role of preparedness for severe accidents, even if they are characterized by very low probability. It has led to intensification of several research and development programs aimed to understand Fukushima, find conclusions, learn and increase the resistance of existing and planned reactors to extreme external and internal circumstances. After Fukushima plenty of studies and analyses are in process and many of them have been completed by vendors, nuclear utilities, governmental agencies, universities and research institutions (Sevón, 2015; Wang et al., 2015; Julin et al., 2014; Lombard et al., 2014; EPR Working Group, 2014; ONR, 2013; Burns et al., 2012; SNL, 2012). Work described in this paper is a contribution to the vast set of activities in this field.

The very strong earthquake and tsunami with similar characteristic as during Fukushima accident, in the case of EPR reactor would results in Loss of Offsite Power and Loss of Ultimate Heat Sink (LUHS). Analyses shows that the plant would withstand such circumstances due to leak tightness and structural robustness of safety related buildings which are designed to be exposed to such external flooding and seismic hazards (Lignini, 2013). Total loss of AC power investigated in this work can be caused by a series of significantly more severe events than those which occurred in Fukushima and PSA studies identify them (Julin et al., 2014; Areva and EDF, 2013a).

In order to withstand more serious sequences and as a part of conclusions after Fukushima, a multiple enhancements were additionally proposed. The EPR reactor safety functions strongly depends on high reliability of power supplies. High quality, redundancy and diversity is basic way to ensure that. Principal lesson after Fukushima is to provide stronger protection and ultimate availability of power sources for long time during SBO type events. In the case of UK EPR, group of five basic resilience enhancements were identified (ONR, 2013). First is improved flooding resistance for emergency electrical AC and DC power sources. Second is increase of autonomy and capabilities of emergency AC and DC power sources. Third is addition of well-defined mobile power means (diesel generators) connection points for both spent fuel pool and reactor. Fourth and fifth areas are: provision of severe accident I&C monitoring of spent fuel pool and connection points for mobile water sources for spent fuel pool and containment spray and heat removal systems (EPR Working Group, 2014; ONR, 2013). Other enhancements are possible and many of them are strongly plant site dependant. Examples of planned modifications for Flamanville-3 and Okiiluto-3 are: allow fuel transfer from EDGs tanks to UDG tanks, increase DC batteries operation time (12–24 h) and provide possibility to fill emergency feedwater system water tanks with water basins located above station level (EPR Working Group, 2014).

There are some general conclusions for most of the plants. Basically stronger physical protection of permanently installed onsite and offsite AC power sources should be provided. Additionally, provision of mobile power supply units in proper amount and configuration is necessary. Long term fuel, water and lubrication oil reserves for emergency power sources have to be ensured. Spent fuel pool cooling by mobile means should also be provided and ability of plant personnel to prepare measures to restore power have to be provided. Accessibility and habitability of the Main Control Room, Emergency Response Centre and local control panels in the plant should be present for long enough time with proper communication system and I&C operation (EPR Working Group, 2014; ONR, 2013).

2. Computer codes

In order to perform computations MELCOR 2.1.5482 computer code was applied. Code was developed by Sandia National Laboratory (SNL) and financed by U.S. Nuclear Regulatory Commission (NRC). MELCOR is integral analysis tool which was initially developed to perform a part of the Probabilistic Risk Assessment (PRA) analysis of nuclear reactors and to evaluate radionuclides releases—source terms (Sehgal, 2012; SNL, 2011ab). Currently MELCOR is becoming best-estimate severe accident tool. Necessity to creation of such a code emerged from the WASH-1400--"The
3. **Plant model**

The investigated reactor design is European Pressurized Water Reactor (EPR), which is four loop pressurized water reactor (PWR). The MELCOR simulations were performed with model based on EPR UK 4590 MWe type unit and MAAP4 was for EPR standard design with 4590 MWe (Areva and EDF, 2013a).
which simulates In-Containment Refueling Water Storage Tank (IRWST) with 2066 tonnes of water. Containment initial pressure was 1.01 bar, 315 K and relative humidity 50% (Areva and EDF, 2013c; SNL, 2011b). Forty-seven Passive Autocatalytic Recombiners (PAR)—based on the parametric default MELCOR model, are located inside the containment, in order to remove hydrogen produced due to the oxidation.

In the EPR model the steam generators with their primary and secondary sides are scaled in the same manner as the broken and intact loops, 1:3. The U-tubes from the primary side are merged into three control volumes with additional two volumes for inlet and outlet chambers (Fig. 1). The secondary side is divided into three volumes representing downcomer, riser with separator part and steam dryer with steam dome (SD) (Areva and EDF, 2013a). Steam generator outlet is connected to the Main Steam Line (MSL) and it is connected to the Steam Header (SH).

The secondary side of steam generator has two types of safety valves—Main Steam Relief Valves (MSRV or MSRT) and Main Steam Safety Valve (MSSV). The first one are opened when pressure in the SG reaches 95.5 bars and second one opens at 104 bars. MSRV valves opening is modeled by hysteresis function and MSSV by ramp function. All valves are connected to the MSL control volumes and they discharge mass to the environment (Areva and EDF, 2013; SNL, 2011a).

Hydrodynamics package (CVH) nodalization for RPV (Fig. 2) has three control volumes for core region and they are distributed radially. There is one volume for bypass, lower plenum (LP), upper plenum (UP), upper head (UH) and downcomer (DC). Reactor core nodalization for core simulations package (COR) is divided into nineteen axial levels (right side of Fig. 2). Four bottom levels are dedicated to simulation of lower plenum, fifth level is for core support plate (CSP). Sixth and nineteen levels are for non-active, bottom and top part of the core. There are twelve levels for active part of the core (from seventh to eighteen levels). Radially core is divided into six rings for LP and five rings for core part of the model (Fig. 2). A conservative decay heat curve and core power density distribution were based on MAAP4 model.

The EPR reactor has special robust design of reactor reflector which is called Heavy Reflector (HR) and its main purpose is to reduce irradiation rate of the reactor vessel and extend its lifetime during normal plant operation and it has ability to absorb large amount of energy during accidents (Areva and EDF, 2013a). Heavy Reflector was merged with core barrel and modeled as a set of heat structures by MELCOR HS package, similarly to typical practice for simulation of core barrel (SNL, 2001).

MELCOR recommended one-dimensional mechanical lower head model was applied. It calculates plastic and thermal strains in each loaded lower head mesh. Lower head mesh has eight nodes and it was composed of twelve segments (SNL, 2011b). Most of the MELCOR2.1 configuration, sensitivity coefficients and modeling parameters were based on SNL MELCOR best practices recommendations developed during SOARCA project (SNL, 2014). Example practices are application of: temperature time-to-failure table (Table 1) for intact but heavily oxidized fuel rods; fuel rods collapse ultimate temperature equal to 2800 K, particulate debris porosity equal 40%, lower head to debris heat transfer coefficient equal to 100 W/m²K and many others.

### 3.2. MAAP model

The EPR model is based on standardized MAAP4 code PWR model. General RCS nodalization is fixed with two loops—single and triple. Model has 14 nodes, one for separated pressurizer model, fours nodes for primary side SG tubes, two hot legs, two

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**Fig. 2.** (a) RPV and core model. Left part of the RPV picture presents CVH nodalization. Right part presents COR package nodalization and heat structures for RPV simulated by HS package. (b) Radial and axial power density profile.
intermediate legs, two cold legs, one lower plenum, one upper plenum and one core node. Each secondary side of SG has two nodes with additional model of separators and dryers. Core model has five rings and thirty-two axial levels. Containment contains ten computational nodes.

MAAP code has simplified thermal-hydraulics formulation which solves lumped parameters differential equations for mass and energy conservation and employs quasi-steady state momentum balance in form of algebraic equations. Otherwise MELCOR solves semi-implicit discretized differential equations for momentum, energy and mass (Vierow et al., 2004; Sehgal, 2012).

4. Scenario and assumptions

The initiating event for the scenario is loss of offsite power. There are some fundamental assumptions for the sequence under consideration:

- Offsite power is not recovered.
- All diesel generators (DG), four Emergency Diesel Generators and two Ultimate Diesel Generators are not available.
- Only in-vessel phase of the accident is under consideration and all computations are stopped when RPV is breached.
- It is assumed that Pressurizer Discharge System (PDS)—system with severe accident dedicated valves installed at the top on the pressurizer are opened when core outlet gas temperature reaches 650 °C. Those valves are powered by long duration (>12 h) SA dedicated batteries which are credited during the scenario (Areva and EDF, 2013c).
- Loss of offsite power leads to the SCRAM of the reactor at the beginning of the accident. It is followed by the loss of Main Feedwater (MFW) and closure of the Main Steam Isolation Valves (MSIV).
- The loss of AC power causes that the Emergency Feedwater System (EFWS), pressurizer cooling sprays and heaters, Containment Heat Removal System (CHRS) are not available.
- Reactor Coolant Pumps (RCP) coast down begins immediately after accident initiation.
- Reactor coolant pumps seals are undamaged (there is no seal LOCA). EPR has an accident dedicated standstill seal system for idle pumps. It provides shaft leak-tightness with no necessity for active seal water supply (Areva and EDF, 2013d).
- It is assumed that there is no primary component creep rupture and only exception is reactor vessel lower head. It has no penetrations and breach due to penetration failure is not possible. Furthermore, thermally induced LOCA and SGTR events are not credited.
- The unavailability of all diesels causes no emergency feed water flow to steam generators (SG) and their dryout.
- Due to the lack of power, active safety injection systems—Medium Head Safety Injection (MHSI) and Lower Head Safety injection (LHSI) are not available.
- Passive accumulators are available.

5. Results and discussion

5.1. Plant steady state

Steady state plant conditions obtained with MELCOR and MAAP are compared in the Table 2. Computed states are in good agreement with relative differences lower than 3%.

5.2. Severe accident analysis

The sequence of events was identified and summarized in Table 3. Important events for MELCOR are shifted in time by about 3–61 min in comparison to MAAP. In the Figs. 3–17 the evolution of the system parameters during the total loss of AC power accident are shown. Presentation and discussion of the results are conducted in this section.

The first phase of the accident starts with LOOP and lasts about 2 h until the SGs complete dryout. Trends of the primary pressure and primary water inventory are shown in Figs. 3 and 4. MELCOR, pressure has different dynamics than MAAP prediction. Initially, it decreases quicker, reaches lower minimum and rapidly increases at the end of the phase (Fig. 3). Primary water inventory stays constant because there is no water loss (Fig. 4).

The secondary side steam generator water level indicating rate of dryout is presented in Fig. 5. MELCOR water level decrease rate is higher in comparison to MAAP with additional discrepancies present at the very beginning and at the end of the dryout process. There is about 30 min dryout shift for MAAP calculation and it is mainly due to smoother drop of the water level at the end

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Time to fuel rod collapse as a function of cladding oxide temperature. Best-estimate recommended MELCOR fuel rods collapse model (SNL, 2014).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cladding temperature (K)</td>
<td>Time to failure</td>
</tr>
<tr>
<td>2090</td>
<td>Infinite</td>
</tr>
<tr>
<td>2100</td>
<td>10 h</td>
</tr>
<tr>
<td>2500</td>
<td>1 h</td>
</tr>
<tr>
<td>2600</td>
<td>5 min</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Table 2</th>
<th>Plant steady state conditions for MAAP and MELCOR.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial conditions</td>
<td>MAAP</td>
</tr>
<tr>
<td>Core power [MWth]</td>
<td>4590</td>
</tr>
<tr>
<td>PZR pressure [bar]</td>
<td>155</td>
</tr>
<tr>
<td>PZR level [m]/Water mass [kg]</td>
<td>6.62/22,500</td>
</tr>
<tr>
<td>SG collapsed water level [m]</td>
<td>14.7</td>
</tr>
<tr>
<td>SG feed water temp. [K]</td>
<td>503.15</td>
</tr>
<tr>
<td>SG secondary side pressure [bar]</td>
<td>77</td>
</tr>
<tr>
<td>Steam flow rate (per SG) [kg/s]</td>
<td>656.9</td>
</tr>
<tr>
<td>Steam flow rate × 3 SG [kg/s]</td>
<td>1920.7</td>
</tr>
<tr>
<td>RCS flow rate (4 loops) [kg/s]</td>
<td>23,156</td>
</tr>
<tr>
<td>RCS flow rate (1 loop) [kg/s]</td>
<td>5789</td>
</tr>
<tr>
<td>RCS flow rate (3 loops) [kg/s]</td>
<td>17,367</td>
</tr>
<tr>
<td>Core inlet temp. [K]</td>
<td>-</td>
</tr>
<tr>
<td>Core outlet temp. [K]</td>
<td>-</td>
</tr>
<tr>
<td>Water mass × 1 SG [kg]</td>
<td>78,000</td>
</tr>
<tr>
<td>Water mass × 3 SG [kg]</td>
<td>234,000</td>
</tr>
<tr>
<td>Water mass RCS [kg]</td>
<td>271,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Sequence of events.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key events</td>
<td>MAAP</td>
</tr>
<tr>
<td>Reactor SCRAM</td>
<td>0 h 00 min</td>
</tr>
<tr>
<td>Start of PZR valves cycling</td>
<td>1 h 48 min</td>
</tr>
<tr>
<td>Broken SG dry</td>
<td>2 h 01 min</td>
</tr>
<tr>
<td>PRT disc rupture</td>
<td>2 h 02 min</td>
</tr>
<tr>
<td>Core uncovery starts—1st time</td>
<td>2 h 36 min</td>
</tr>
<tr>
<td>Tmax 650 signal reached</td>
<td>2 h 57 min</td>
</tr>
<tr>
<td>SA dedicated valves opening (PDS)—pressurization</td>
<td>2 h 57 min</td>
</tr>
<tr>
<td>Accumulator injection onset</td>
<td>3 h 05 min</td>
</tr>
<tr>
<td>Accumulator depletion</td>
<td>3 h 21 min</td>
</tr>
<tr>
<td>Core uncovery starts—2nd time</td>
<td>3 h 46 min</td>
</tr>
<tr>
<td>Oxidation onset</td>
<td>4 h 11 min</td>
</tr>
<tr>
<td>Start of core melting</td>
<td>4 h 13 min</td>
</tr>
<tr>
<td>Start of core relocation to lower head</td>
<td>6 h 20 min</td>
</tr>
<tr>
<td>Vessel failure</td>
<td>6 h 50 min</td>
</tr>
</tbody>
</table>
of the phase (Fig. 5). Lower primary side pressure and faster secondary side dryout suggest that the heat transfer between primary and secondary side predicted by MELCOR is more intensive. It is an effect of MAAP4 and MELCOR thermal-hydraulics and SG model differences.

The thermal-hydraulics related processes predicted by MELCOR are shifted in time due to shorter SGs dryout. There is no steam generator water makeup and shortly after its isolation pressure rises (Fig. 7). Then, MSRVs start their cyclic operation when pressure reaches 95.5 bars. This process continues until the initiation of the RCS depressurization. The heat is intensively transferred from the primary side, water turns into steam and leaves the system through MSRVs.

Fig. 3. Primary system pressure (in the pressurizer).

Fig. 4. Reactor coolant system water inventory.

Fig. 5. Collapsed water level in the steam generator. ZWUS for intact and ZWBS for broken loop.

Fig. 6. Broken (TBUS) and unbroken (TGUS) gas temperature inside steam generator.

Fig. 7. Broken (PBS) and unbroken (PUS) steam generator pressure.

Fig. 8. Gas temperature at core outlet.

Fig. 9. Water level in the core. BAF, Bottom of Active Fuel; TAF, Top of Active Fuel.
Further accident phase starts with initiation of PSV valves cycling and ends with depressurization (Table 3). The first apparent effect of the shorter dryout is an earlier initiation of the pressurizer safety valves cycling (Fig. 3 and Table 3). During the dry-out, SGS loss ability to fulfill their primary task—to completely remove the heat from the primary side. A less efficient heat removal causes primary water heat-up and pressure increase, which inevitably leads to PSV valves operation.

Primary coolant system is heavily emptied before depressurization, due to PSV valves operation (Fig. 4). Before the beginning of the depressurization there is only about 70 tonnes of water in the RCS for both codes. Pressure history (Fig. 3) shows similar trends during that phase with time span of valve cycling for MELCOR being shorter (4140 s) in comparison to MAAP4 (4698 s) (Fig. 3). Due to this difference, the low pressure phase of the accident starts practically in the same moment with PDS initiation time differing only by 142 s.

Core gas outlet temperature was used as an indicator of severe accident and trigger for the PDS valves opening (Fig. 8). After about 3 h gas reaches temperature of PDS activation signal (650 °C) and it leads to primary system depressurization (Fig. 3). After depressurization, primary water drops to 50 tonnes and primary pressure heavily decreases. When pressure reaches 45 bars passive accumulators start water injection to the cold legs and as an effect approximately 100 tonnes of water is transferred to the system (Fig. 4). Accumulator injection takes 572 s and 960 s for MELCOR and MAAP respectively. It is because, MELCOR does not predict short plateau in water inventory as MAAP does (Fig. 4) and it transfers about 10 tonnes more water to the primary system. MELCOR pressure drops faster during the injection and because its rate is pressure difference induced, timing is different and plateau exists. What is remarkable after the end of the water injection, RPV water dryout starts and it has higher rate for MELCOR (Fig. 4). Those effects are visible when core water level is under consideration (Fig. 9).

Differences in temperature and pressure histories occur in steam generators after depressurization (Figs. 6 and 7). Although, they are not significant for the course of the accident due to very small heat transfer between primary and secondary side. Temperature and pressure decrease are mainly due to heat exchange with the containment. Its rate is controlled by the modeling of heat structures connecting SG with containment and by the fact that MELCOR has only one control volume for the containment. Steam generators water level increase to a small extent 5 h after the onset of the accident.

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**Fig. 10.** Fuel cladding temperatures. In MELCOR case for inner core ring and four top axial levels (Fig. 2). For MAAP it is maximum temperature and it does not indicate the fuel element collapse time.

**Fig. 11.** In-vessel hydrogen production.

**Fig. 12.** In-vessel hydrogen production rate.

**Fig. 13.** In-core hydrodynamic fluid volume fraction (indicator of core blockage) evolution for the MELCOR core degradation.
The core degradation phase initiates at the beginning of the secondary core uncover (Figs. 9 and 10). Fuel and cladding temperature starts to rise due to the lack of proper cooling. The oxidation threshold temperature is reached (∼1500 K) after about 4 h and very intensive exothermic zirconium oxidation reactions start to generate large amount of heat and hydrogen gas (Figs. 10 and 11).

In-vessel cumulative hydrogen production is presented in Fig. 11. The production rate for MELCOR was calculated as derivative of cumulative hydrogen production (Fig. 12). Until the vessel rupture, MAAP model produces about 200 kg more hydrogen than MELCOR. During initial half an hour of oxidation phase, hydrogen production is similar for two codes (Fig. 12) and it is about 550 kg. Afterwards, MELCOR intensive oxidation heavily drops at 4 h 35 min and ceases at 4 h 50 min. Otherwise, MAAP in-core oxidation intensity decreases at 4 h 50 min but until 5 h 30 min it is not suppressed completely (Fig. 11). High oxidation rate occurs again only when hot corium relocates to the lower plenum. A very small amount of hydrogen is produced during first core uncover and most of the hydrogen production results from secondary uncover (Figs. 9 and 11). Hydrogen production rate is in general lower for whole oxidation phase for MELCOR than for MAAP4 (Figs. 11 and 12). The anticipated physical explanation of MELCOR lower hydrogen production is due to faster secondary uncovering resulting in earlier core degradation. After 4 h 06 min MELCOR core water level drops below BAF and for MAAP4 it occurs after 4 h 55 min (Fig. 9). Otherwise, oxidation starts after 4 h 00 min and 4 h 11 min for MELCOR and MAAP respectively. Hence, water and steam are directly available in the core for longer time in the MAAP. The physical explanation of an earlier uncovering is presented in one of the subsequent paragraphs. Moreover, less steam produced at the surface of water inside the core has an possibility to leave RPV by different flow path without contact with degrading cladding. The more rapid core uncover leads to enhanced core degradation rate and an earlier core blockage phenomena. The changes in the fuel geometry effectively blocks steam inflow into the core and stops oxidation. Zero hydrogen production rate was observed after 4 h 50 min (Fig. 11) and it is coincident with the moment of the total core blockage for gas flow (Fig. 13 (#3)).

The recent EPRI comparison study between MAAP5 and MELCOR shows that MAAP produces two-to-three times less hydrogen during in-vessel phase of the core melt scenario in the case of BWR reactors (EPRI, 2014). EPRI describes that the effect is due to differences in the core degradation evolution with modeling of changes in the geometry (areas for oxidation) and flow blockage (EPRI, 2014). It is important for steam flow through the core during early degradation when the hydrogen production is expected to be intense. What is interesting, in our work we did not observed such discrepancy for PWR reactor. However, MELCOR hydrogen production is in fact lower but prior to its termination, oxidation

accident (Fig. 5). Effect is present due to the steam condensation process and it was observed for both codes.

The highest fuel and cladding temperatures are present in upper parts of the core (Fig. 2). Fuel temperature starts to rise after about 2 h 30 min when the first core uncover begins (Figs. 9 and 10 and Table 3). Due to delayed water injection, top MELCOR predicted temperature is about 1000 K and for MAAP it is about 200 K higher. Water injected from accumulators effectively suppress temperature rise, core is reflooded and intensively quenched (Fig. 9). This state lasts for about 45 min and 35 min for MELCOR and MAAP respectively (Fig. 10).
rate it is relatively similar (Figs. 11 and 12). In the publicly available literature, MELCOR and MAAP4 usually produce similar hydrogen inventory for PWR reactors. An example calculation are available for total loss of Feedwater (H2 sequence) for French PWR 900 MWe for the end of in-vessel phase of the accident. Hydrogen production obtained with MAAP4.0.7, ASTECV2.0 and MELCOR1.8.5 (after 5 h) are: 410, 390 and 400 kg respectively (Lombard et al., 2014; De Rosa, 2008). Similar result can be found for SBO/TMLB’ Zion PWR simulations (after 5 h) with MAAP4.0.5, SCDA/RELAP5 MOD3.3 and MELCOR1.8.5 with detailed and simple CVH core nodalizations, respectively: 490, 510, 530, 470 kg of hydrogen (Vierow et al., 2004; SNL, 2001). For those two codes, it suggest that there is substantial difference between BWR and PWR core degradation modeling from oxidation point of view. One of the possible explanations is the difference in canisters degradation evolution and what is undeniable PWRs have no canisters (EPRI, 2014).

In the MELCOR simulation presented in this work, higher core recovery rate and lower oxidation rate can be caused by the simplified CVH nodalization of the core. Applied modeling simplifies thermal-hydraulic phenomena and leads to possible under-predictions of the hydrogen production. In the case of detailed CVH nodalization, PWR SBO model should produce similar hydrogen masses for MELCOR and MAAP (Vierow et al., 2004). Moreover for the simple nodalization predicted inventory can be lower (SNL, 2001). Code developers from Sandia recommends (it is not demanded) to develop CVH core model with one CVS per two core axial levels (SNL, 2014). In general MELCOR in-vessel hydrogen production is very sensitive to huge set of uncertain parameters and for same reactor it can give wide span of the results (Gauntt et al., 2001). MAAP and MELCOR have different oxidation and core degradation models and it is also potential source of differences. MELCOR applies parabolic oxidation correlation by Urbanic–Heidrick and MAAP4 uses Baker–Just correlation combined with Cathcart model (Wang et al., 2014a,b). Those two models are not very different but they are very sensitive to the temperature variation (as oxidation does) and even slight difference in oxidation surface temperature prediction across the core can impact the calculation. Temperature is controlled by heat transfer with fluid and it seem to be reasonable that thermal-hydraulics nodalization could have an impact onto fluid behavior and in consequence on oxidation rate. In MELCOR code special dT/dz model dedicated to predict core fluid temperatures for coarse CVH nodalization containing many COR nodes is available (and was used). Although, it is still possible that code simplifies gas heat transfer, leading to under or over-prediction of the temperatures (SNL, 2011b).

Fuel elements lose their integrity and collapse immediately after entering into temperature range 2600–2800 K (Fig. 10). The degradation starts in the upper central part of the core and process propagate thought it creating complex debris beds with evolving molten pools. Material of the fuel assemblies is melting, candling, refreezing, slumping and successively moving downward.

MELCOR predicts about 10 tons of material being transferred to the lower plenum before the massive relocation preceded by the core plate failure. Otherwise, MAAP does not predict any material transfer before the massive relocation. A part of debris and molten material created in the upper parts of the core relocates downwards and settles on the lower core structures. Hot material during relocation is intensively cooled by remaining water and it promotes steam creation. In the case of MELCOR, the process is more efficient and secondary core recovery is quicker (Fig. 9). After the complete core uncover, the hot material collected on the core plate is no longer cooled. MELCOR due to its modeling allows molten materials, i.e., remained superheated unoxygened metals or control materials to be transferred to the lower plenum before core plate failure (SNL, 2011b, 2014). Those interacts with water, forms debris and settles on the lower head. In this process, water in the lower plenum is intensively transformed into steam which leaves the RPV (Fig. 9). Phenomenology described above is the main reason of earlier core recovery predicted in MELCOR calculation. The mass of molten material and debris relocated to the lower plenum is presented in Fig. 13. For MELCOR, it can be observed that the massive relocation occurs approximately 1 h earlier in comparison to MAAP (Table 3).

During the first massive relocation there are approximately 40 tons of material more transported to the lower plenum in the MELCOR case (Fig. 13). MELCOR relocation takes more time due to sequenced failure of the core support plate rings. Corium starts to relocate after 5 h 21 min and it takes more than 1 h to breach the vessel. The lower head failure is predicted to occur after 6 h 23 min as a creep-rupture process in one of the sideward nodes and it leads to calculation termination. The side rupture indicates the interaction with metal layer. Different MELCOR simulations performed for the ex-vessel phase (beyond the scope of this article) predict the series of the failures of other lower head nodes and effectively continuous corium discharge into the reactor pit.

In MAAP, the first relocation occurs after 6 h 20 min due to sideward heavy reflector (HR) melt-through (Areva and EDF, 2013c; Sehgal, 2012). After the first relocation corium stays in the lower plenum for 30 min only, until the initial RPV rupture occurs. MAAP has special mode of RPV breach with initial sideward breach due to interaction with molten metal layer and subsequent breach (Lombard et al., 2014). The subsequent breach occurs about 7 h 20 min (Fig. 13) and the second relocation due to core plate failure is predicted after 7 h 45 min. The plate does not have to support the whole corium mass and it lasts for longer time.

Due to its specific design, Heavy Reflector was modeled in MELCOR by the set of heat structures (Fig. 2) and only relocation through the core plate is possible. It induces observed differences in the core relocation results. MAAP has dedicated heavy reflector model with melt-through capability and MELCOR does not (Sehgal, 2012). What is worth to mention, MELCOR has ability to model TMI-2 like sideward corium relocation, through the core shroud, bypass and further to lower plenum (SNL, 2011b). For EPR situation it is different in TMI-2. In the HR there are hundreds of low diameter cooling holes and corium cannot relocate massively through them because there is not enough space. Hence, it is expected that corium will melt-through HR to the downcomer and slumps down to the lower plenum (Areva and EDF, 2013c). EPR was modeled as typical MELCOR PWR core with downcomer not being a part of core degradation model (COR package) and in consequence it was not possible to model relocation through it (SNL, 2011b). As a response to that result it would be desirable to make an attempt to model downcomer as a part of the core package model. It is not clear though if this approach is possible. Another interesting and important attempt would be to add HR as an additional mass to the COR package with downcomer modeled traditionally. These modifications should change the course of the events and in our opinion it would consequently increase time to corium relocation and time to vessel rupture.

MELCOR and MAAP lower plenum corium behavior and lower head interaction models are different and it is the principal reason of the faster lower head failure after mass relocation in the MAAP case. MAAP4 applies, three layer model of material in the lower plenum. The top layer is made of particulate debris and it covers molten metal layer which is placed on the layer of oxide molten pool. The oxide pool is additionally coated by an isolating crust. Code effectively models lower plenum as one node (EPRI, 2014; Lombard et al., 2014). In MELCOR different debris materials are located within a lower plenum nodalization structure and code calculates the distribution of those materials among the complex nodalization. In EPR case it has 6 rings and 4 axial levels. Lower plenum possible constituents are similar to MAAP: conglomerate debris, particulate debris, oxidic pool, metallic pool and crust.
Nevertheless, MELCOR for debris and pools is more mechanistic than MAAP models (EPRI, 2014; Lombard et al., 2014; SNL, 2011b). Those two codes predict debris layer or crust between oxide pool and lower head and due to that first rupture is not expected in the bottom part of the lower plenum. MELCOR and MAAP in order to predict creep-rupture failure apply the Larson-Miller logic based models (EPRI, 2014; SNL, 2011b). In two calculations under consideration, metal layer is main contributor to vessel failure. Metal layer promotes vessel failure due to the so-called focusing effect (Sehgal, 2012).

The time history of the pressures, steam and hydrogen masses in the containment are compared in Figs. 15–17. The increase of the pressure in the containment starts after PRT tank rupture disc break. In MELCOR case, PSV valves cycling time span after PRT disc rupture is longer (Fig. 15). Time period between start of PSV cycling to PRT disc rupture for MELCOR is 894 s and for MAAP is 840 s, hence dynamics of PRT loading seems to be comparable. For the first few minutes after disc rupture, steam mass released to the containment effectively increase pressure. Afterwards, pressure stabilizes at constant level (about 2 bars) and it is mainly due to quasi-equilibrium between periodical steam release by PSV valves and steam condensation. In general containment pressure level is controlled by steam content for all scenario phases (Figs. 15 and 16).

In the course of the depressurization process MELCOR predicts high pressure peak (Fig. 15) and it is an effect of one control volume containment model (Tills et al., 2009). MAAP4 containment nodalization is more detailed and gives different response during steam outflow. After the end of depressurization peak disappears, steam content falls down and MELCOR pressure is lower due to efficient condensation (Figs. 15 and 16).

Discrepancy between pressure peak predictions at the corium massive relocation to the lower plenum was observed (Figs. 3 and 15). Simulation with MAAP predicts about 4 MPa peak in RCS whereas MELCOR gives only 1 MPa. Peak properties strongly depends on amount of water in the lower plenum but it is also dependant on corium fragmentation and molten corium heat transfer formulation (SNL, 2014; Humphries et al., 2010). MAAP4 water mass in lower plenum is larger and during relocation it produces more steam and generate higher pressure peak (Figs. 4 and 9). Finally modeling of corium coolant interactions during relocations are governed by different models and similar peak could not have been expected. Pressure peak is visible as change in steam inventory for the containment (Fig. 16) and water mass in RCS (Fig. 3). It is weak pressure disturbance from the RCS point of view (Fig. 3). In the containment pressure peaks related to the relocation are lower than 0.5 bars (Fig. 15). Nevertheless, those values are not significant and higher pressure peak occurs during RCS depressurization (Fig. 15). Pressure in the containment during in-vessel phase is well below design limit (5.5 bars) and there is no threat to the containment integrity due to over-pressurization.

Hydrogen mass in the containment is presented in the Fig. 17. Results are close for both codes with mass increasing during core degradation phase. After 4.5 h when intensive oxidation stops inventory decreases—due to the operation of the Passive Autocatalytic Recombiners. MAAP uses recombiners model based on the actual Areva PARs, otherwise default code model was used in MELCOR simulations (Sehgal, 2012). Therefore, it is possible to conclude that the observed good agreement is rather incidental. It results from lower recombination rates predicted with MELCOR as the hydrogen mass released into the containment is also lower.

6. Conclusions

The paper presents the in-vessel phase simulation results of the total loss of AC power severe accident for EPR reactor. Comparison of results obtained by two different integral Severe Accident codes—MAAP4 and MELCOR was performed. Differences in the physical models and modeling approach were discussed. It shows that results are comparable even due to substantial differences in code capabilities. Similar timing and course of the events during in-vessel phase of the accident was observed (Table 3). From reactor safety point of view principal result is comparable time to vessel breach—end of the in-vessel phase. MELCOR predicts 27 min earlier RPV rupture than MAAP. Another important result from safety point of view is the estimated time to initiation of SAMG depressurization procedure and both codes are in good agreement with 11 min difference.

The MELCOR simulation predicts lower hydrogen in-vessel production than MAAP code (Fig. 7). Differences in core Thermal-Hydraulics and core degradation sequence are main contributors to that effect. Different core degradation evolution is basically an effect of more intensive water dryout during secondary core uncover.

MELCOR predicts earlier and different mode of the corium relocation to the lower plenum with more mass being transported. Corium inventory accumulated in lower plenum before lower head breach are different by about 40 tonnes. It is believed to be an effect of different modeling of EPR heavy reflector. MAAP4 has dedicated heavy reflector model with a possibility of melt-through calculation and relocation to the downcomer and MELCOR does not.

Reactor Pressure Vessel failure calculated by MELCOR occurs after six and half hour after accident initiation and it is half an hour earlier than predicted by MAAP4. Codes have different RPV breach modeling, MELCOR predicts one failure due to creep-rupture and MAAP predicts initial and subsequent creep-rupture failures.

Generally core degradation, lower plenum phenomena as well as hydrogen production are sensitive to changes in large amount of usually very uncertain parameters like candling heat transfer, debris porosity, oxidation coefficients, etc. (Humphries et al., 2010; Gauntt et al., 2001). Hence, principal recommendation is to perform sensitivity analysis to get wider perspective. It is crucial step and without it we should not state final conclusions about safety of nuclear reactor, its behavior during severe accident and potential consequences. Worthy to find that different integral codes for the same nuclear reactor give comparable results and it provides a justification to further development of the model and conduction of more detailed comparison of MELCOR with different codes like MAAP, ASTEC or SCADAP/RELAP.

Presented MELCOR model is still under development with a more detailed RPV model, new containment, alternative HR modeling, new PARs and other features. Further development is important, especially if authors would like to work with wide range of alternative scenarios, with consideration of ex-vessel phases and in order to perform reliable radionuclides source term calculations.

Acknowledgements

The publication was created in the framework of a strategic project NCBR: “Technologies for the development of safe nuclear energy”, Research Task No. 9 entitled: “Development and implementation of safety analysis methods in nuclear reactors during disturbances in heat removal and severe accident conditions.” The publication was created also thanks to the fruitful cooperation between Warsaw University of Technology and AREVA. The authors would like to thank for AREVA contribution and to Pascal Gandrille and Werner Schmidt for numerous hints.

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