A STUDY ON TRANSIENT HEAT TRANSFER OF THE EU-ABWR EXTERNAL CORE CATCHER USING THE PHASE-CHANGE EFFECTIVE CONVECTIVITY MODEL

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ABSTRACT

In advanced designs of Nuclear Power Plants (NPPs), for mitigation of severe accident consequences, on the one hand, the In-Vessel Retention (IVR) concept has been implemented. On the other hand in other new NPP designs (Generation III and III+) with large power reactors, the External Core Catcher (ECC) has been widely adopted. Assessment of ECC design robustness is largely based on analysis of heat transfer of a melt pool formed in the ECC. Transient heat transfer analysis of an ECC is challenging due to (i) uncertainty in the in-vessel accident progression and subsequent vessel failure modes; (ii) long transient, (iii) high Rayleigh number and complex flows involving phase change of the melt pool formed in an ECC.

The present paper is concerned with analysis of transient melt pool heat transfer in the ECC of new Advanced Boiling Water Reactor (ABWR) designed by Toshiba Corporation (Japan). According to the ABWR severe accident management strategy, the ECC is initially dry. In order to prevent steam explosion flooding is initiated after termination of melt relocation from the vessel. The ECC full of melt is cooled from the top directly by water and from the bottom through the ECC walls. In order to assess sustainability of the ECC, heat transfer simulation of a stratified melt pool formed in the ECC is carried out. The problem addressed in this work is heat flux distribution at ECC boundaries when cooling is applied (i) from the bottom, (ii) from the top and from the bottom. To perform melt pool heat transfer simulation, we employ Phase-change Effective Convectivity Model (PECM) which was originally developed as a computationally efficient, sufficiently accurate, 2D/3D accident analysis tools for simulation of transient melt pool heat transfer in the reactor lower plenum. Thermal loads from the melt pool to ECC boundaries are determined for selected ex-vessel accident scenarios. Performance of the ECC, efficiency of severe accident management (SAM) measures and procedures are evaluated based on results of PECM simulation and severe accident analysis.

KEYWORDS
Severe accident, core catcher, heat transfer, Severe Accident Management (SAM)

1. INTRODUCTION

Over decades the nuclear power has shown a significant role in electricity power generation, energy security, becomes an important solution for global warming. Due to Fukushima accidents development of nuclear power in the world have been significantly affected. Lessons learnt from the Fukushima have confirmed that the nuclear power should rely on knowledgeable human resources, strong regulation systems and robust designs to ensure safety. On the one hand, designs of NPPs have been improved significantly in the last 20 years in order to strengthen the defense in depth. Recently the External Core Catcher (ECC) have been widely adopted for several designs of reactors Gen III+. For instance, the concept of BWR90+ ECC has been modified and applied to the European Advanced Boiling Water Reactor (EU-ABWR) designed by Toshiba (Toshiba's ECC) [1]. On the other hand, adequacy of Severe Accident Management (SAM) Guidelines (SAMGs) and Emergency Operating Procedures (EOPs) should be verified to prevent disasters such as "Fukushima" in the future [2]. Largely, SAMGs have been developed based on experiences and accident analysis which are subject of significant phenomenological (epistemic) uncertainty. Therefore, identification of governing factors, analysis and prediction of accident progression are of paramount importance for determination of adequate SAMGs.

Analysis and prediction of accident progression have been a subject of intense research in the past. The Fukushima accident confirmed once again that core melting and Reactor Pressure Vessel (RPV) failure [3] are not purely hypothetical events. Core melt behavior under the reactor of Fukushima Unit 1 is still not yet understood. Several studies have been performed in the past to predict core melting progression of BWRs [4,5]. However, large uncertainty remains due to complex phenomena.

Severe accident analysis starts from the in-vessel accident progression which in turn will define ex-vessel melt behavior. For instance, vessel failure modes and timing, discharged melt characteristics (e.g. melt jet velocity and diameter) and the total amount of melt mass, large single or multiple melt discharge, etc. are the influencing factors on the ex-vessel melt progression [6]. Vessel failure modes and timing for Boiling Water Reactors (BWRs) has been studied [7,8], using the newly developed model for simulation of melt pool heat transfer, namely the Phase-change Effective Convectivity Model (PECM) [9,10]. The vessel creep study has shown that there are 2 modes of vessel failure that is localized creep and global creep. The other type of vessel failure is penetration failure and falling down (instrumentation tubes, control rod guide tubes in the lower plenum of BWRs) [8]. Each type and mode of the RPV failure may result in different ex-vessel melt progression. The vessel failure modes and discharging melt characteristics are key factors for determination of appropriate SAM measures and SAMGs.

Previously the core catcher has been designed for BWR90+. Performance of the BWR90+ core catcher was studied using the MVITA code [11]. Heat transfer simulation for a stratified melt pool (7.5 cm thick metal layer) by the MVITA has shown that with water cooling from outside the core catcher is able to sustain and stabilize the melt. The thermal margin remains substantial [12]. Following the concept of BWR90+ core catcher, the Toshiba's EU-ABWR core catcher is aiming at fulfilling the safety requirements in Europe. The Toshiba's ECC is designed for collection and stabilization of the ex-vessel melt. Water is injected to the ECC from below (outside cooling) and the top (top flooding). A recent study

[1] has been performed to analyze functioning of the ECC under melt jet impinging, mechanical and thermal loads. Melt jets impinging may largely depend on melt characteristics and mass. Water injection into the ECC (outside cooling and top flooding) is accepted as SAM measures for the ABWR. It was shown that the ECC is capable of withstanding different loads, and stabilization of melt. In the study, heat transfer simulation has focused on determination of margins to the Critical Heat Flux (CHF). However, no detailed analysis of ABWR in-vessel accident progression and subsequent ex-vessel accident scenarios leading to formation of a melt pool in an ECC is found in the open literature.

Concerning severe accident research in the past, beside development of models and tools for prediction, many experiments have been performed to study ex-vessel melt behavior. Recently a series of experiments was carried out, that is pouring of high melting temperature binary oxidic melt into a shallow water pool followed by liquid melt spreading under water [13,14,15]. Energetic spontaneous Stratified Steam Explosions (SSE) have been observed repeatedly in the tests. Strong instability of the melt-water interface and formation of premixing layer were observed with subsequent SSE.

Given phenomenological uncertainty in the accident progression, it is important to consider and analyze in-vessel accident progression and subsequent ex-vessel scenarios for an ABWR. SAM measures such as water injection should be based on detailed and sufficiently accurate analysis of in-vessel accident progression and ex-vessel scenarios. Early water injection may result in accumulation of a certain amount of water in the core catcher, as a result later melt discharges may lead to an SSE under a shallow layer of water. Late top flooding water injection with sufficient water flow rate may also result in another kind of Steam Explosion (SE).

In this paper, transient heat transfer simulation of melt pool in an EU-ABWR ECC is performed to determine thermal loads. Based on the results of simulation, analysis and identification of impacting factors on the efficiency of SAM measures relevant to the ECC are carried out. The structure of the paper is as follows. The second section describes the Toshiba's EU-ABWR ECC structure, accident scenarios taken into analysis, the tools used for heat transfer simulation, computational domain and initial, boundary conditions applied for simulation. The third section presents results of the PECM simulations, analysis and discussions on impacting factors on SAM measures. The fourth section concludes the paper with few insights drawn from the study.

2. EU-ABWR EXTERNAL CORE CATCHER AND ACCIDENT SCENARIOS

This section contains description of the external core catcher of Toshiba's ABWR, description of the methodology and tools used for heat transfer simulation of a melt pool formed in the core catcher. Other relevant information such as accident scenarios and configurations, initial and boundary conditions applied for heat transfer simulation etc. are also expressed.

2.1. External core catcher of the Toshiba's EU-ABWR

The core catcher is installed on the bottom floor, under the RPV of ABWR (Fig. 1). The core catcher consists of a round basin (Fig. 2), lower inclined cooling channels, an annulus riser, an annulus downcomer and a central water chamber (Fig. 3) [1]. It has a comparatively large diameter of about 10 m. This axisymmetric structure is intended to provide the uniform accumulation and cooling of the core melt as design purpose. Due to the special structure of the ECC, it helps effective cooling due to large surface-to-volume ratio of the core melt.

The main component of the ECC is the refractory layer, which is installed on the surface of the basin. The material of the refractory layer is selected from metallic oxides, that is alumina (Al_2O_3). The ECC functions are actuated passively, and it has no active components inside the containment. Water is injected to the catcher from below (outside cooling) and from the top (top flooding) for cooling and stabilizing corium melt relocated in the core catcher.

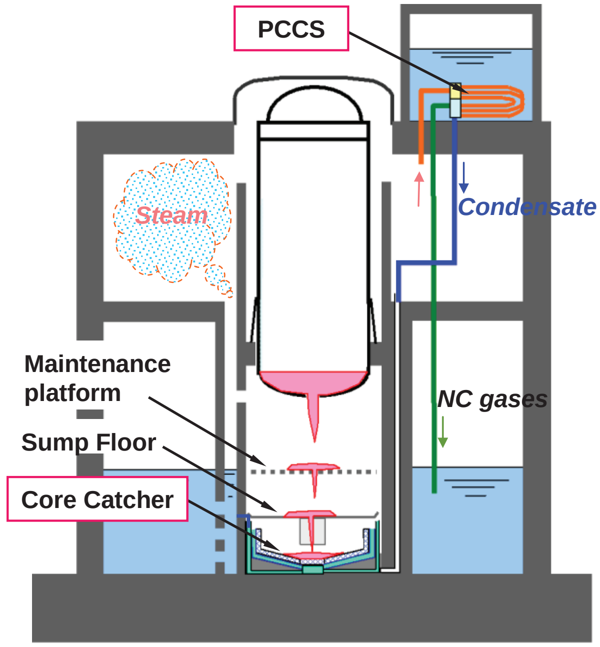

Figure 1. ABWR configuration and arrangement of the external core catcher [1].

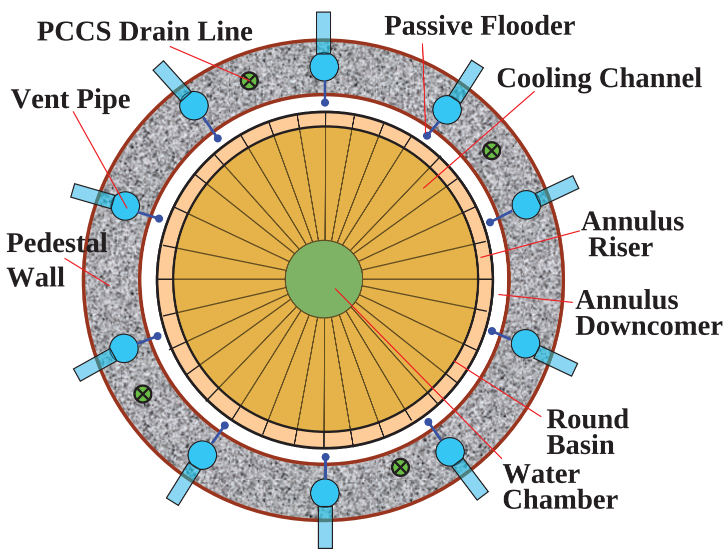

Figure 2. Top view of the external core catcher [1].

As the refractory material (alumina) is used in the core catcher, one of the important characteristics of alumina is temperature dependence of thermal conductivity. At low temperature, alumina is more conductive (high thermal conductivity, for instance at 500 K (227 ^{o}C) its conductivity is about 12 $W.m^{-1}.K^{-1}$. As temperature is increased, thermal conductivity of alumina is decreased (5 $W.m^{-1}.K^{-1}$ at 1500 K) (Fig. 4). This feature of the refractory material (alumina) may have significant effect on the heat removal capability of the core catcher. This effect will be taken into account in the study.

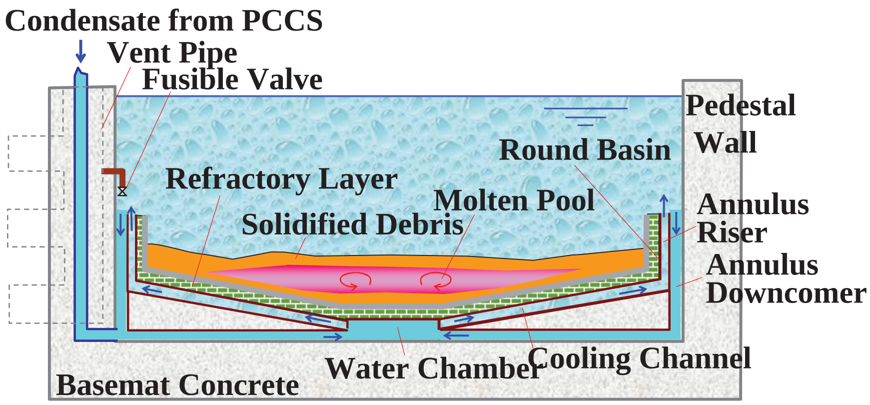

Figure 3. Configuration of the core catcher, side view [1].

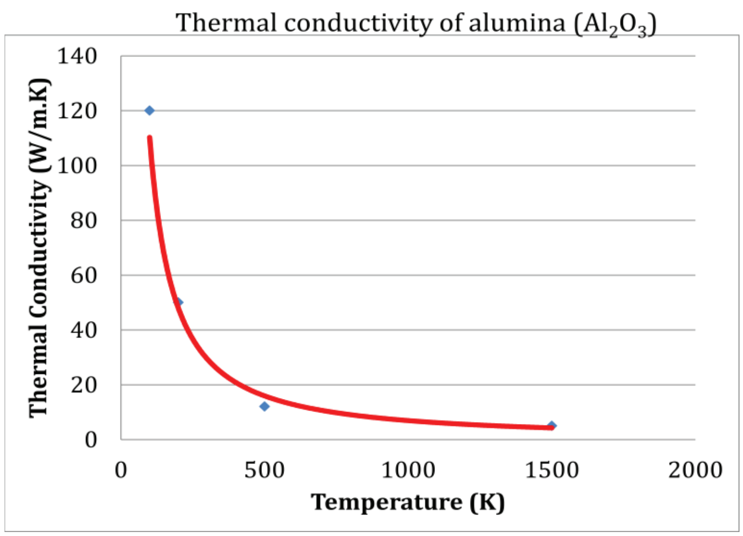

Figure 4. Temperature dependency of thermal conductivity of alumina (Al_2O_3).

The core catcher is designed to cope with all possible accident scenarios of EU-ABWR. It is the final barrier to mitigate severe accident consequences, to avoid fission product release to environment. Therefore functioning and efficiency of the core catcher is of paramount importance for accident analysis. The next part describes the tools which are used for heat transfer simulation in an EU-ABWR ECC.

2.2. The Phase-change Effective Convectivity Models

To describe heat transfer of decay-heated oxidic pool, and the metal layer on top (Rayleigh-Benard convection), the Phase-change Effective Convectivity Models (PECMs) have been developed and validated [9,10,16]. The PECMs are capable of capturing the effect of natural convection in a decay-heated melt pool with a metal layer atop (a stratified melt pool).

In this study, the oxidic melt pool PECM and metal layer PECM are the main tools used in this study for simulation of heat transfer in the Toshiba's EU-ABWR ECC. The PECMs use the Fluent platform for simulation while not solving Navier-Stokes equations. The energy conservation equation is solved by the PECMs by determination of characteristic velocities using empirical correlations. In the PECM applying for heat transfer simulation of oxidic melt pool, empirical directional Steinberner-Reineke heat transfer correlations [17] are employed to determine characteristic velocities:

$$Nu_{up} = 0.345.Ra'^{0.233} \quad (1)$$

$$Nu_{sd} = 0.85.Ra'^{0.19} \quad (2)$$

$$Nu_{down} = 1.389.Ra'^{0.095} \quad (3)$$

For description of Rayleigh-Benard natural convection heat transfer, the metal layer PECM employs the other empirical correlations for determination of characteristic velocities, that is the Globe-Dropkin correlation [18] for describing upward heat transfer:

$$Nu = 0.069 Ra^{0.333} \mathrm{Pr}^{0.074} \quad (4)$$

$$3\text{x}10^5 < Ra < 7\text{x}10^9; \qquad 0.02 < Pr < 8750$$

and the Churchill-Chu correlation [19] for describing sideward heat transfer:

$$Nu_{side}^{1/2} = 0.825 + \frac{0.387\, Ra^{1/6}}{\left[1+\left(0.492/\mathrm{Pr}\right)^{9/16}\right]^{8/27}} \quad (5)$$

The PECMs (i.e. the PECM for oxidic melt pool simulation and the metal layer PECM for simulation of metallic layer on top of oxidic melt pool) have been validated against several experiments with a wide range of governing parameters such as Rayleigh number [20,16]. Both PECMs can be employed simultaneously for simulation of heat transfer of a stratified melt pool. They have been used for simulation of melt pool heat transfer in the VVER-1000 lower plenum [21].

2.3. PECM simulation of EU-ABWR ex-vessel accident progression

It is postulated that a core melting accident happens in an ABWR. Without adequate cooling, corium melt is accumulated in the lower plenum. Due to thermal attack to the RPV, the vessel wall fails [7,8]. Due to the difference in melting temperatures of oxide and metal (e.g. steel), core melt including liquid metal and oxidic melt/solid particles discharges and accumulates in the core catcher.

In an EU-ABWR, the uranium fuel and full zirconium oxidation may create about 250 tons of mixed oxide as maximum. The total mass of steels from the reactor internal structures is about 200 tons. Taking into account the potentially available oxidic and metallic masses which can be relocated into the core catcher, the present study considers a stratified melt pool which consists of 0.8m thick lower layer (e.g. oxidic) and 0.2m thick metal layer atop (Fig. 5). According to the density of materials presented in Table I, the 0.8m thick oxidic melt pool may contain about 240 tons of mixed oxide/metal in the lower part of the core catcher. To examine the focusing effect, a thin metal layer (0.2m thick) atop the oxidic pool is taken into consideration.

It is assumed that core melt including liquid metal and mixed liquid/solid oxidic particles is discharged into the core catcher. Due to lower liquidus temperature, liquid metal from the vessel may be discharged to the core catcher earlier. A stratified melt pool is formed. Due to the difference in melting temperatures of oxide and liquid metal (steel) and heat exchange, the oxidic part of the melt pool is solidified creating a debris bed. The lower debris bed may consist of solid oxidic particles and liquid metal (a matrix of liquid metal and oxidic particles). The liquid metal layer is floating to the top. Due to presence of liquid metal inside, the debris bed is considered to have larger thermal conductivity than that of poor oxidic melt.

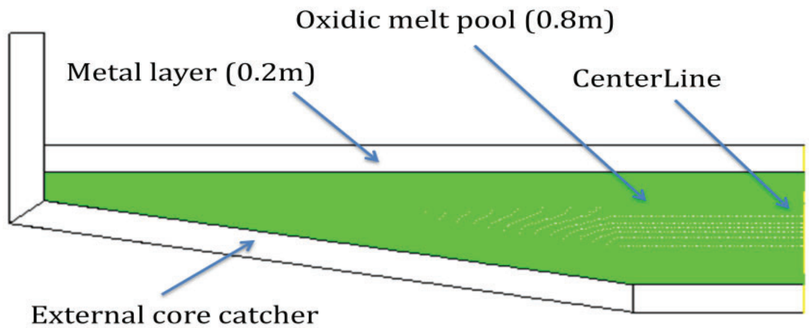

Figure 5. Computational domain of the PECM simulation.

Table I. Properties of core melt materials and refractory material of core catcher

Material properties	**Oxidic melt** [22]	**Metallic layer** [23]	**Alumina** [1]
Density, kg/m^3	8600	7000	3800
Thermal conductivity, $W.m^{-1}.K^{-1}$	3	18	Varying along graph in Fig. 4
Specific heat capacity, $J.kg^{-1}.K^{-1}$	485	430	1172
Solidus/liquidus temperature, K	2750/2700	1727/1671	2302

The computational domain for heat transfer simulation is presented in Fig. 5. The thickness of the refractory layer is 0.2m. Material properties used for simulation are expressed in Table I. The initial and boundary conditions are as follows. Initial temperature of the debris bed is about 2000 K (solid phase), temperature of the metal layer is about 1800 K (liquid phase). Two scenarios are taken into consideration in this study. First, only outside water cooling is provided for the core catcher. The outside wall temperature is water saturation temperature (383 K). No top flooding is considered for the top metal layer, only radiation heat transfer condition is applied for this top wall of metal layer. In the following parts of paper, the first scenario is named "Case 1B". Second, both outside water cooling (to core catcher outside walls) and top flooding (to metal layer top surface) are considered. We assume that the outside walls and top wall of the metal layer are applied to Dirichlet boundary conditions (isothermal with water saturation temperature). The second scenario is named "Case 1C" in the following sections and graphs.

It is worth noting that the assumed configuration of stratified melt pool is considered as an example for heat transfer simulation to support further analysis of SAM measures. 2D configuration which is conservative due to large ratio of volume to cooling surface is considered. In the next section, results of PECM heat transfer simulation are presented and analyzed.

3. RESULTS OF PECM HEAT TRANSFER SIMULATIONS AND DISCUSSIONS

3.1. Accident progression without/with water injection on top

In this section, results of PECM transient heat transfer simulation for 2 scenarios are presented.

For the accident scenario without water cooling from the top surface of melt pool (only water cooling from the outside walls of the core catcher, case 1B), melt pool temperature is presented in Fig. 6. It is seen that in 9000 sec (2.5 hours) after melt relocation into the catcher, temperature of debris bed (oxidic melt pool) exceeds 2870 K (superheat is of about 120 K). Metal layer has high temperature, higher than 2302 K which is the melting temperature of alumina. Figure shows high temperature of the catcher wall close to the metal layer (focusing effect). However, due to heat removal by radiation from the top surface, temperature of the metal layer is kept much lower than that of the oxidic melt pool (Fig. 6).

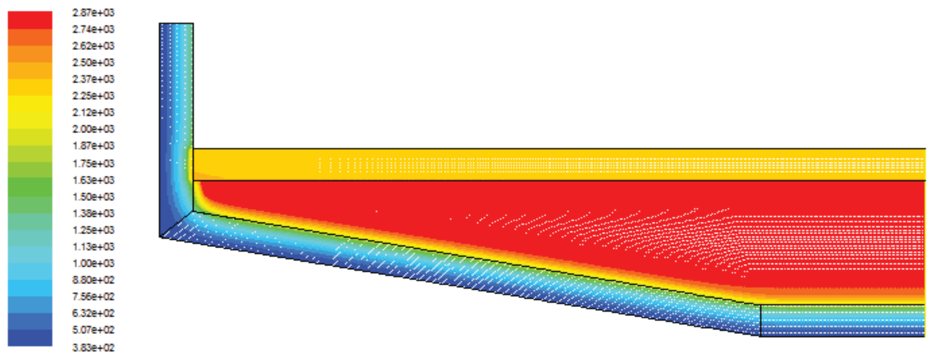

Figure 6. Temperature contour of the melt pool and core catcher in 9000 sec (case 1B).

Fig. 7 shows temperature profile of the oxidic melt at the centerline. The PECM captures the effect of natural convection which causes a flat bulk temperature profile. The oxidic melt pool is enveloped by crust where conduction is dominated (conduction areas in Fig. 7, see Fig. 9). The effect of Rayleigh-Benard convection (natural convection) is well captured by the PECM and clearly shown in Fig. 8.

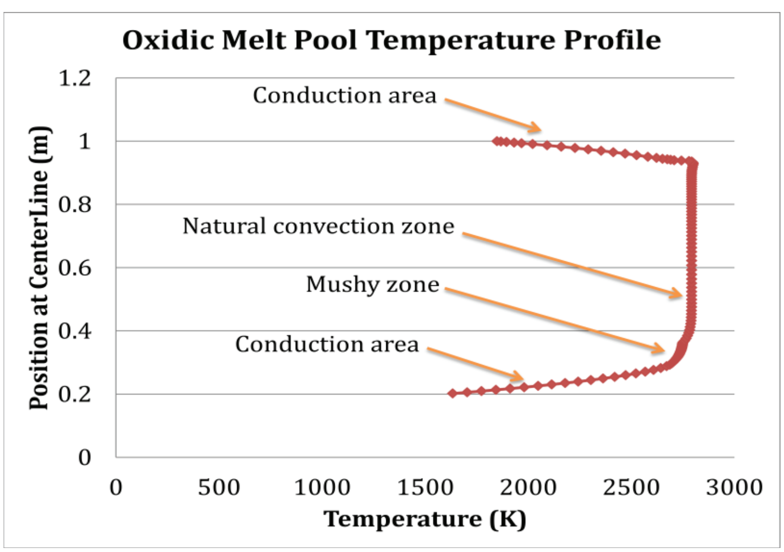

Figure 7. Temperature distribution at centerline of oxidic melt pool at 6000 sec (case 1B).

Fig. 9 shows melt pool configuration at 7000 sec. At the first moment of relocation, a layer of crust is available along the catcher internal walls due to their low initial temperatures. However, at 7000 sec, the crust in between the metal layer and catcher wall is disappears, the catcher wall becomes eroded due to melting at high temperature (higher than liquidus temperature of alumina).

In the scenario “case 1C”, due to efficient heat removal by water on the top of metal layer (that is the assumption that sufficient water on top efficiently removes heat and keeps the surface at low temperature), the metal layer is almost solidified in 6000 sec (Fig. 10). Thick crust layer envelopes the oxidic melt pool. Clearly, the melt is stabilized in the core catcher in this scenario (both outside cooling and top flooding measures are applied).

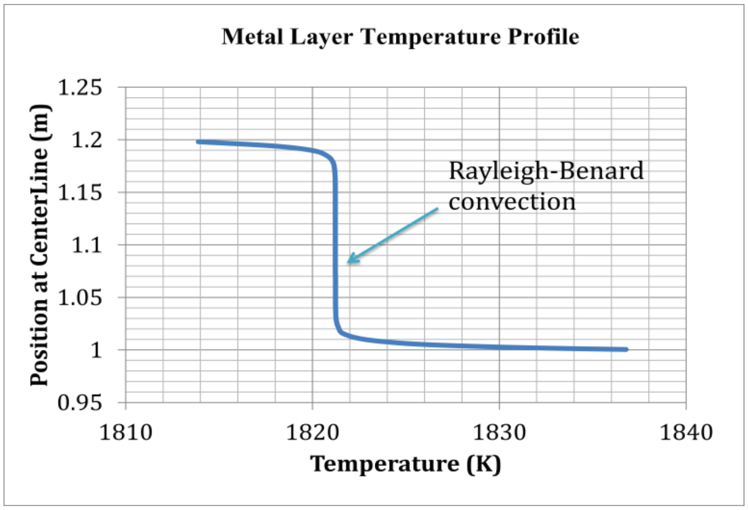

Figure 8. Temperature distribution along centerline of metallic layer at 6000 sec (case 1B).

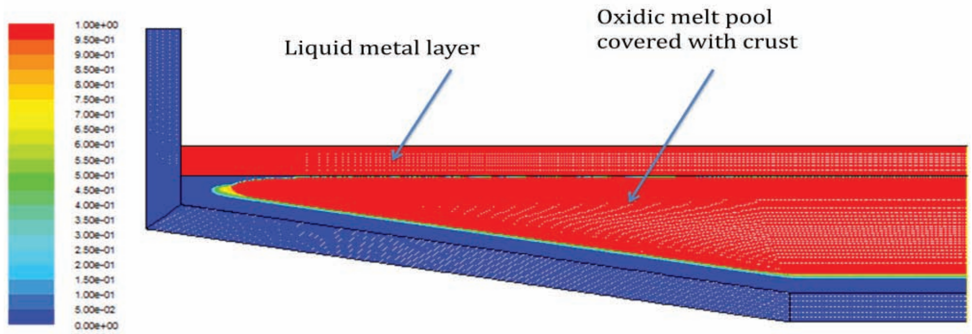

Figure 9. Melt pool condition at 7000 sec (about 2 hours) of case 1B.

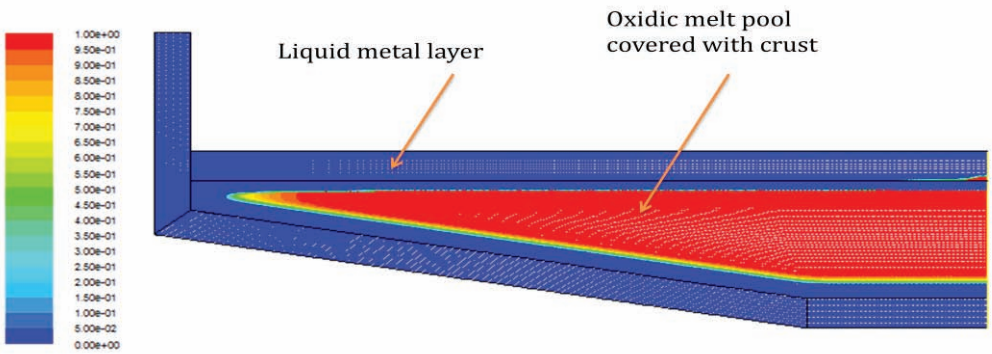

Figure 10. Melt pool condition at 6000 sec of case 1C.

3.2. Analysis of accident progression and efficiency of SAM measures

Averaged transient temperatures of oxidic debris bed (melt pool), metal layers are presented in Fig. 11. Graphs show that transient temperatures of oxidic debris bed (melt pool) in two scenarios are almost coincident, i.e. debris bed (melt pool) temperature is nearly independent of SAM cooling measures. The melt pool may be stabilized in several hours when heat removal at boundaries is adequate.

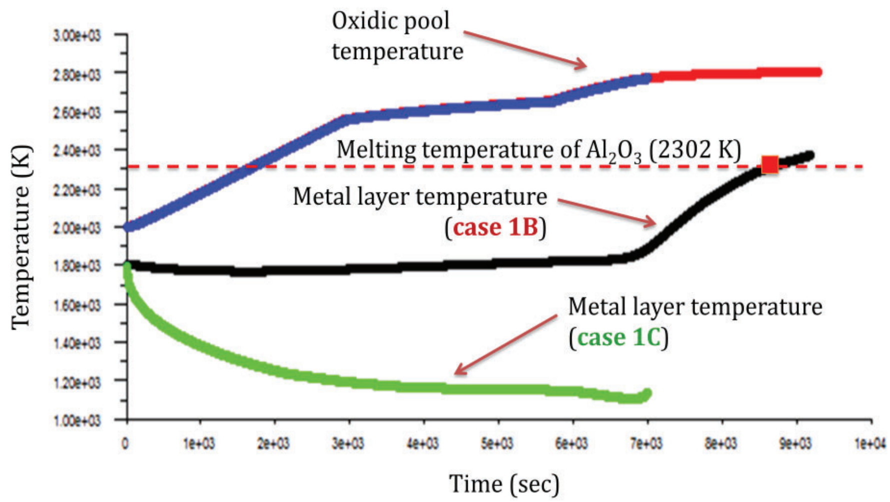

Figure 11. Transient temperatures of oxidic and metal layer pools (averaged along centerline).

Graphs of temperatures of the metal layers look different (Fig. 11). In the case of water cooling on the top surface of metal layer (top flooding), metal layer temperature is decreased fast, making the layer solidified (Fig. 10). Without water cooling from the top (radiation heat transfer only, case 1B), temperature of metal layer increases. The rate of temperature growth increases dramatically when the crust between the oxidic melt pool and metal layer becomes thinner (Fig. 9). At about 8500 sec, metal layer temperature exceeds the melting temperature of alumina (see Fig. 11), the refractory material is eroded. Fig. 12 shows that the focusing effect is observed at the catcher wall (outside) cooled by water.

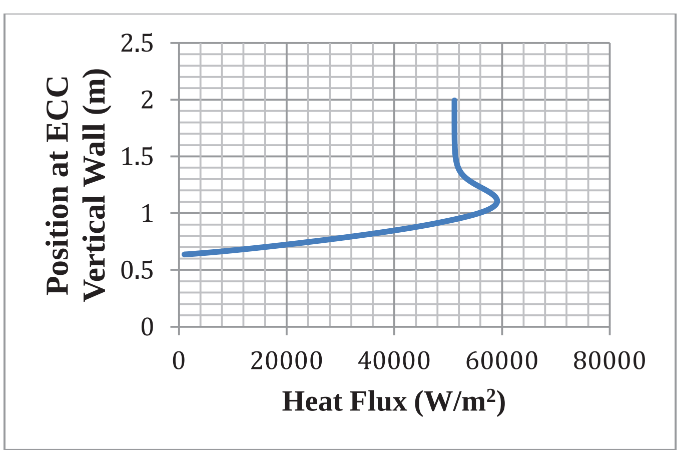

Figure 12. Heat flux distribution at the ECC external surface (upper part) at 8500 sec (for case 1B).

Fig. 12 also shows that even the focusing effect is observed, the heat flux at the catcher wall is small in the first hours after relocation. Looking into transient averaged heat fluxes at the catcher outside wall (vertical wall connected with the metal layer) (Fig. 13), it is shown that in the case of top flooding, the heat flux is stabilized in about 1.2 hour (4200 sec). However, if water is not available on the top surface of melt pool (i.e. dry metal layer), the heat flux at the catcher vertical wall is continuously increased. The increase will be faster when the catcher vertical wall is melted and eroded at the metal layer place. This increase might eventually lead to exceeding the Critical Heat Flux (CHF), and the core catcher failure may take place. It is instructive to note that that core catcher wall failure (if expected) happens at quite late time, likely more than 3-4 hours after relocation, even for a large amount of melt accumulated in the core catcher (we are considering a large stratified melt pool with a thin metal layer atop). The property of refractory material may effect significantly on catcher wall failure probability. However, core catcher wall failure is still questionable, this is a subject of further study.

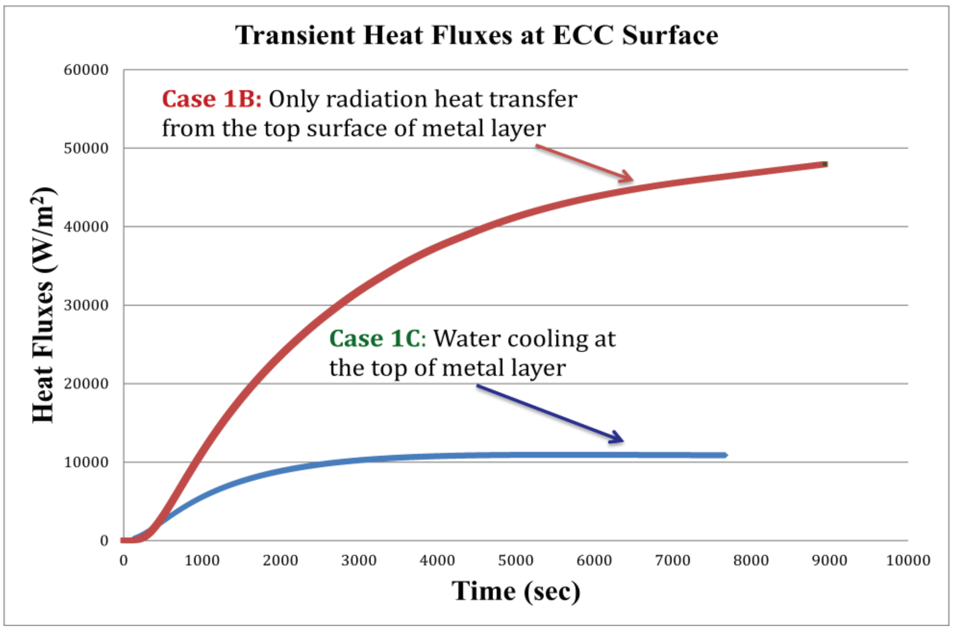

Figure 13. Averaged transient heat fluxes of different scenarios at ECC external surface.

It is worth to note that currently PECM lacks a model for prediction of the process of alumina ablation. Such model is a subject of the future work and is out of the scope of the present study.

3.3. Implication of the results for the ex-vessel accident progression

Results of PECM heat transfer simulation suggest that combination of water cooling from outside walls and top surface of melt pool (mixed outside cooling and top flooding) can rapidly stabilize the melt pool inside the Toshiba's EU-ABWR core catcher. Further investigation might address the question about potential influence of the transient boundary conditions at the top of the metallic layer, e.g. by considering transient water flooding and different boiling regimes.

Lacking water cooling from the top surface of melt pool, heat removal (convection from outside walls of core catcher and radiation heat transfer from the top melt pool surface) is insufficient to stabilize the melt temperature within considered simulation time frames. Potential failure of the core catcher due to thermal attack from the hot metal layer as a result of the focusing effect may take place. This question should be addressed in the future study.

The water injection timing and flow rate should be considered in SAM measures. Early water injection may lead to accumulation of a large amount of water in the core catcher and result in energetic melt-coolant interactions during melt releases from the vessel. Therefore the amount of water available in the core catcher should be controlled. Top flooding water injection may also lead to SSE. The probability of SSE depends on melt pool condition (i.e. superheat) and water temperature [13,14,15]. With a small rate of flooding, water in ECC will be kept at near saturation point providing unfavorable conditions for SSE. If water injection flow rate is high, and water subcooling are large then SSE is more likely to happen.

Based on given results of PECM heat transfer simulation and analysis above, few conclusions can be drawn:

- In-vessel accident progression analysis to identify vessel failure modes, timing, melt characteristics and melt discharge scenarios etc. is essential for ex-vessel risk scenarios consideration;
- Without water injection into the top surface of metal layer, the core catcher is able to sustain without melting of refractory material for a certain time, at least few hours (3-4 hours) after melt relocation can be expected; It is expected that the core catcher can hold the core melt without top flooding;
- Activation time of the top flooding water injection SAM measure is important for consideration;
- The water flow rate accepted during the top surface flooding is an important parameter for consideration in SAM measure procedure and SAMG;
- In the case of accepting top flooding, it is suggested to control the amount of injected water available in the core catcher in case of a multiple melt discharge scenario;
- In the case of water cooling applied to both lower walls and top surface of melt pool in the core catcher, examination of heat fluxes exceeding the CHF due to the focusing effect is not an issue. Due to large surface of water cooling (large diameter core catcher), the melt will be well stabilized in the core catcher.

4. CONCLUDING REMARKS

In the present paper transient heat transfer has been performed for a stratified melt pool formed in the Toshiba's EU-ABWR external core catcher. The Phase-change Effective Convectivity Model (PECM) tools (both the oxidic and metal layer PECMs) were used for simulations.

Results of PECM simulation suggest that water cooling applied to outside of the catcher walls, and top melt pool surface simultaneously is able to stabilize the core melt. The heat flux at the core catcher vertical outside walls is small. Without water cooling from the top of melt pool, thermal attack due to the focusing effect eventually may make the core catcher failed. Further study is needed to examine if the core catcher is capable of stabilizing the melt only with water cooling from outside. In the case the top flooding is necessary, the top surface flooding SAM strategy is important for consideration of the possibility of Stratified Steam Explosion (SSE) [13,14,15].

Results of the work suggest that scenarios of melt release from the reactor vessel, flooding activation time, water flow rate and available water amount in the core catcher are important for robustness of SAM measures applied in the EU-ABWR.

NOMENCLATURE

Arabic ***Greek***

Nu	Nusselt number, $Nu = \frac{qH_{pool}}{k\Delta T}$	*ρ*	Density, kg/m^3
Pr	Prandtl number, $\Pr = \nu / \alpha$	ΔT	Temperature difference, K
Ra'	Rayleigh number (internal), $Ra' = \frac{g\beta Q_v H_{pool}^5}{k\nu\alpha}$	*α*	Thermal diffusivity, m^2/s, $\alpha = \frac{k}{\rho . C_p}$
Ra	Rayleigh number, $Ra = \frac{g\beta\Delta T H^3}{\nu\alpha}$	*ν*	Kinematics viscosity, m^2/s
q	Heat flux, W/m^2	*β*	Thermal expansion coefficient, 1/K
H	Height (or depth/thickness) of a volume or melt pool/fluid layer, m		***Subscripts and superscripts***
k	Conductivity, W/m.K	*up*	Upward
Q_v	Volumetric heat source, W/m^3	*down*	Downward
g	Gravitational acceleration, m/s^2	*side*	Sideward
C_p	Specific heat capacity, J/kg.K	*pool*	Pool

ACKNOWLEDGMENTS

The authors thank to Toshiba Cooperation (Japan) for their support and providing data, to the Hanoi University of Science and Technology (HUST), Vietnam and the Division of Nuclear Power Safety (NPS), the Royal Institute of Technology (KTH), Sweden for collaboration.

REFERENCES

1. R. Hamazaki, T. Nakagawa, N. Katagiri, M. Tahara, M. Komuro, T. Tobimatsu, Y. Suzuki, T. Kutita, "Evaluation on Core Melt Retention in Core Catcher of Toshiba's EU-ABWR", *Proceedings of the International Congress on Advances in Nuclear Power Plants (*ICAPP*) 2011*, Nice, France, 02-05 May, 2011, Paper 11414 (2011).
2. G. Vayssier, "Present day EOPs and SAMG – Where do we go from here", *Nuclear Engineering and Technology* **44**(3), April (2012).
3. http://rt.com/news/242701-japan-fuel-melted-fukushima/ (2015).
4. R. Gauntt, D. Kalinich, J. Cardoni, J. Phillips, A. Goldmann, S. Pickering, M. Francis, K. Robb, L. Ott, D. Wang, C. Smith, S. St.Germain, D. Schwieder, C. Phelan, "Fukushima Daiichi Accident Study (Status as of April 2012)", *Report of Sandia National Laboratories*, July (2012).
5. R. Gauntt, D. Kalinich, J. C. Phillips and J. Phillips, "MELCOR Simulations of the Severe Accident at the Fukushima 1F1 Reactor", *Proceedings of Severe Accident Assessment and Management: Lessons Learned from Fukushima Dai-ichi San Diego California*, November 11-15 (2012).
6. P. Kudinov, S. Galushin, S. Yakush, W. Villanueva, V.-A. Phung, D. Grishchenko, N. Dinh, "A Framework for Assessment of Severe Accident Management Effectiveness in Nordic BWR Plants," *Probabilistic Safety Assessment and Management PSAM 12*, June 22-27, 2014, Honolulu, Hawaii, Paper 154 (2014).
7. W. Villanueva, C.-T. Tran, and P. Kudinov, "Coupled Thermo-Mechanical Creep Analysis of Boiling Water Reactor Pressure Vessel Lower Head", *Nucl. Eng. Des.* **249**, pp.146-153 (2012).
8. W. Villanueva, C.-T. Tran and P. Kudinov, "Analysis of Instrumentation Guide Tube Failure in a BWR Lower Head", *Proceedings of the 9th International Topical Meeting on Nuclear Thermal-*

Hydraulics, Operation and Safety (NUTHOS-9), Kaohsiung, Taiwan, September 9-13, Paper 0268 (2012).

9. C.-T. Tran, T.-N. Dinh, "The effective convectivity model for simulation of melt pool heat transfer in a light water reactor pressure vessel lower head. Part I: Physical processes, modeling and model implementation", *Progress in Nuclear Energy* **51**, pp. 849-859 (2009).
10. C.-T. Tran and T.-N. Dinh, "The effective convectivity model for simulation of melt pool heat transfer in a light water reactor lower head. Part II: Model assessment and application", *Progress in Nuclear Energy* **51**, 860-871 (2009).
11. V.-A. Bui. and T.-N. Dinh, "Modeling of Heat Transfer in Heat-Generating Liquid Pools by an Effective Diffusivity-Convectivity Approach", *Proceedings of the 2nd European Thermal-Sciences Conference*, Rome, Italy, pp.1365-1372, 29-31 May (1996).
12. T.-N. Dinh and T.G. Theofanous, *Ex-vessel Melt Coolability and Retention*, University of California, Research Report CRSS-02/03, pp. 150p, Santa Barbara, USA (2002).
13. P. Kudinov, D. Grishchenko, A. Konovalenko, A. Karbojian, S. Bechta, "Investigation of Steam Explosion in Stratified Melt-Coolant Configuration", *The 10th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-10)*, Okinawa, Japan, December 14-18, 2014, Paper 1316 (2014).
14. D. Grishchenko, A. Konovalenko, A. Karbojian, V. Kudinova, S. Bechta, and P. Kudinov, "Insight into steam explosion in stratified melt-coolant configuration", *The 15th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH 15*, May 12 to 17, 2013, Pisa, Italy, Paper 599 (2013).
15. A. Konovalenko, A. Karbojian, and P. Kudinov, "Experimental Results on Pouring and Underwater Liquid Melt Spreading and Energetic Melt-coolant Interaction", *Proceedings of the 9th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-9)*, Kaohsiung, Taiwan, September 9-13, 2012, Paper 0303 (2012).
16. C.-T. Tran, P. Kudinov, "The Effective Convectivity Model for Simulation of Molten Metal Layer Heat Transfer in a Boiling Water Reactor Lower Head", *Journal Science and Technology of Nuclear Installations* **2013**, Article ID 231501, May (2013).
17. U. Steinberner and H.H. Reineke, "Turbulent Buoyancy Convection Heat Transfer with Internal Heat Sources", *Proceedings of the 6th Int. Heat Transfer Conference*, Toronto, Canada, Volume 2, 305-310 (1978).
18. S. Globe and D. Dropkin, "Natural-Convection Heat Transfer in Liquid Confined by Two Horizontal Plates and Heated from Below", *J. Heat Transfer* **81**, pp.24-28 (1959).
19. S.W. Churchill and H.S. Chu, "Correlating Equations for Laminar and Turbulent Free Convection from a Vertical Plate", *Int. J. Heat Mass Transfer* **18**, pp.1323-1329 (1975).
20. C.-T. Tran, P. Kudinov and T.-N. Dinh, "An Approach to Numerical Simulation and Analysis of Molten Corium Coolability in a BWR Lower Head", *Nucl. Eng. Des.* **240**(9), pp.2148–2159 (2010).
21. N.-T. Phan, T.-N. Nguyen, C.-T. Tran, "Application of the Effective Convectivity Model for Melt Pool Heat Transfer Simulation in a VVER-1000 Reactor Lower Head", *Proceedings of the 9th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-9)*, Kaohsiung, Taiwan, September 9-13 (2012).
22. T.G. Theofanous, C. Liu, S. Addition, S. Angelini, O. Kymalainen, T. Salmassi, "In-vessel Coolability and Retention of a Core Melt", DOE/ID-1046, November (1994).
23. J.L. Rempe, S.A. Chavez, G.L. Thinnes, C.M. Allison, G.E. Korth, R.J. Witt, J.J. Sienicki, S.K. Wang, L.A. Stickler, C.H. Heath, and S.D. Snow, Light Water Reactor Lower Head Failure, Report NUREG/CR-5642, Idaho Falls (1993).