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Review of the doctoral dissertation of Eleonora Skrzypek, M.Sc. Eng.
"Thermo-hydraulic modeling of a steel metal layer on top of a corium pool in a PWR under severe accident condition"

1 Introduction

In this section a description of the thesis is provided. We discuss the content of each chapter with the emphasis on the relevant issues presented in the thesis, scope and main achievements.

1.1 Significance

Humankind is facing its biggest challenge yet - climate change caused by the industrial emissions of CO_2 and other greenhouse gases, mainly due to the use of fossil fuels for energy supply and transport. Urgent changes are needed in the energy sector in order to avoid major climate disaster. Nuclear power is a CO_2 free non-intermittent source of both electrical and thermal energy. In combination with renewable sources of energy, such as wind, solar and hydro, nuclear power can satisfy societal needs in energy, including the energy needed to offset past and distributed sources of CO_2 emissions (such as wildfires) and to cope with consequences of already ongoing climate change, while maintaining living standards.

Public safety was a concern from day one for the use of nuclear power. In normal operation, nuclear power plants do not produce any emissions. However, in case of a sever core melting accident significant amounts of radiative fission products can be released into the environment. Reliable prevention and mitigation of severe accidents is extremely important to enhance public acceptance and thus replace fossil fuel power generation with nuclear power.

The reviewed thesis addresses physical phenomena at the in-vessel stage of the severe accident progression that are important for determining the possibility of retaining core melt, and thus most of the fission products, inside the vessel (so called in-vessel retention). As such, the work aims to provide an important contribution to the overall sustainability of nuclear energy.

1.2 Scope of the thesis work

The thesis consists of 7 Chapters and includes the list of the author papers published in journals (4) and in conference proceedings (3).

Chapter 1 provides a brief overview of possible initiating events for the severe accidents as well as important phenomena for in- and ex-vessel accident progression and relevant experimental investigations done in the past. Then the author reviews more in depth phenomena relevant to the thermal hydraulics of core melt pool including the "focusing effect" and its impact on the In-Vessel Melt Retention (IVMR) as a severe accident mitigation strategy.

Chapter 2 presents results of station blackout (SBO) accident analyses carried out with system codes namely MELCOR (developed at ANL) and PROCOR (developed at CEA). The differences in predictions by different codes are identified, and parametric sensitivity analysis is carried out with PROCOR.

Chapter 3 is dedicated to a critical review of the literature on the solidification-melting and free convection phenomena in a metallic layer heated from below. Limitations of the available empirical correlations and potential of CFD modeling approaches are discussed.

Chapter 4 describes a combination of 0D and 1D models for transient simulation of solidification and melting phenomena in the metallic layer. The chapter also provides results of extensive testing of different models' performance.

Chapter 5 extensively discusses equations that govern free convection of fluid in a metallic layer. The focus is on the derivation of non-dimensional form of equations and resulting non-dimensional scaling criteria. A case that shows the impact of the Marangoni effect is also presented.

Chapter 6 investigates the behavior of liquid metallic layer at various conditions including the configurations prototypic for a severe accident. First the BALI-Métal experiment (that was carried out with water was addressed to validate the models. Then a new set of correlations was derived for the metallic layer of various heights relevant to severe accident conditions.

Chapter 7 is the summary of the of the work that presents main conclusions and outlook.

1.3 Main achievements

Following main achievements presented in the work can be mentioned:

- A study, that was carried out using MELCOR and PROCOR codes for an SBO scenario in an EPR with variation of several parameters that are relevant to the vessel failure phenomena, showed importance of modeling of the heat transfer characteristics in the metal layer.
- A combination of reference (1D) and lumped (0D) approaches for transient solidification and melting phenomena in a metal layer were developed and integrated with the PROCOR platform. The analysis of test problems showed some limits of applicability of the simplified approaches based on the analytical temperature distributions in solid material.
- Derivation of the non-dimensional equations for the metal layer heat transfer is carried out with extensive scaling analysis that provided useful insights into possible different regimes.
- It was demonstrated that the Marangoni effects can be neglected for metal layers thicker than ~3-4 cm.
- Validation of CFD code ANSYS Fluent with different turbulence models was carried out against (i) BALI – Métal test with water coolant, and (ii) DNS data for low Pr conditions with sodium coolant. The results suggest that with proper selection of a RANS k-w model results of the tests can be reproduced with a reasonable accuracy.

- Heat transfer simulations in a metallic layer at prototypic conditions has been carried out using validated codes and models with variation of the problem parameters, mainly thickness of the layer and heat fluxes. Nu correlations are proposed based on the CFD analysis results for the metallic layer.

2 Critical and Editorial Comments

In this section we provide comments for the thesis text including editorial ones.

General recommendations:
While the work presented in the thesis is overall of high scientific quality, some rearrangements in the presentation of the work would be very helpful to a reader who wants to understand the main achievements and the impact of the thesis. Specifically, it is recommended to restructure the content of Chapters 1 and 7. In Chapter 1 it is recommended to introduce separate sub-sections to describe explicitly in succinct terms (i) general motivation for thesis work, (ii) goals for the whole thesis work, and (iii) tasks, that have been undertaken in order to achieve the goals. In Chapter 7 it is recommended to highlight and clearly separate as sub-sections (i) summary of what was done in order to achieve the goals of the thesis, (ii) main achievements, i.e., what new methodological developments were proposed, what new results that have been obtained, (iii) conclusions of what was found from the analysis that has impact on the motivation for the thesis work, and finally (iv) outlook on what could be done in the future given the main findings and achievements of the thesis work.

Page 25: "Usually, the triggering factor is connected to the exit core temperature, which after reaching 650◦C is initiating the phase with the core melting processes [1]." It should be clarified here that the core exit temperature mentioned here is used as a criterion for transition from EOPs to SAMGs in the accident management for PWRs.

Page 25: "residual power" more common term would be decay heat.

Page 28: Table 1.1 in Phase I "Oxidation of fuel cladding" more accurately it is an onset of oxidation, not complete oxidation. "Fuel rod heating to about ~1400◦" it is rather 1200C as it is mentioned below Figure 1.2 and in Figure 1.3.

Page 32: "…which will fasten the safety barrier to fail…" use other wording, e.g. "which might accelerate failure of the safety barrier…".

Page 33: "…high-pressure jet formation while entering the ex-vessel phase…" high pressure jet is not necessarily formed in this case. It will depend on depressurization of the primary system.

Page 32: "…can produce a highly energetic reaction – FCI (Fuel Coolant Interaction). The reaction can be mechanical and turn into a phenomenon called steam explosion" change of wording is needed. E.g., "can produce a highly energetic reaction – FCI (Fuel Coolant Interaction) also called steam explosion."

Page 32: "The event effect could be damaging and result in the RPV and surrounding structures' immediate destruction" different wording would be needed. E.g., "The steam explosion could result in the damage containment structures". Also, in this context, it would be good to clearly separate in-vessel steam explosion and so-called alpha mode of containment failure (where highly subcooled water is usually unavailable) and ex-vessel steam explosion (where presence of highly subcooled water is possible).

Page 32: "probability of a such event is low [3], especially the failure of the vessel's upper head and its cause to fail the containment was found to be of very low (10−3) conditional probability [16]." Please find original references to the works of Theofanous where the issue of alpha mode containment failure was resolved from risk perspective using ROAAM approach.

Page 33: "The debris layer coolability is a matter of discussions and investigations, but the numerous research [17], [18], [19] show that 32 the debris cooling rate is limited and depends upon various debris bed characteristics uncertain parameters." The coolability of the debris bed has been addressed in depth phenomenologically in the works of S. Yakush et al. and from risk perspective in the works by S. Galushin et al. References to those wors would be appropriate here for a reader.

Page 33: "The load on the vessel wall is a result of four mechanical effects [4]:" (i) "thermo-mechanical phenomena" would be more appropriate in this context, (ii) in the list one could add partial ablation and thinning of the RPW wall.

Page 33: "the LP and the vessel wall (at the temperature of around 45–55 ◦C)". How vessel wall can be of so low temperature? Please, change wording to clarify which temperature do you mean.

Page 34: "The one criterion that is investigated during the Nuclear Power Plant safety assessment is the probability of the RPV break during the accident analysis, as it is considered the second physical barrier in the NPP." Please, change wording to clarify. E.g., instead "The one criterion" but "One of the phenomena…".

Page 34: "The break of the RPV results in the increased probability of the FP releases and more severe consequences to the public." It is not so much about RPV break, but about corium release into environment. The vessel (or primary coolant system) is actually expected to be depressurized (by opening valves, or "naturally" by the failure of the surge line under the influence of high temperature (>1600C) gases and at high pressure). Thus, the second barrier will be "broken" in any case once core degradation starts and some fission products will be released into the containment. It is about the threat to containment integrity that corium released from the RPV can present.

Page 34: "The problem of the RPV break time evaluation becomes important due to the fact that it is the cornerstone of the defense-in-depth approach and should be specified as close to reality as possible." It should be mentioned here that the timing is important because of the so called Large Early Release Frequency (LERF) is the key part for the public safety.

Page 35: First two paragraphs of Section 1.2.
It should be emphasized that all phenomena described in the paragraph are mostly relevant when vessel is cooled from the outside. If vessel is not cooled (or has penetrations in the lower head), it is quite likely that vessel or one of the vessel penetration (especially if penetrations are not cooled from inside) will fail before formation of a large melt pool will take place see e.g. see some works of W. Villanueva et al. (2012-2016) and also

Torregrosa, C., Villanueva, W., Tran, C.-T., and Kudinov, P., "Coupled 3D Thermo-Mechanical Analysis of a Nordic BWR Vessel Failure and Timing," 15th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH 15, May 12 to 17, 2013, Pisa, Italy, Paper 495.
Goronovski, A., Villanueva, W., Tran, C.-T., and Kudinov, P., "The Effect of Internal Pressure and Debris Bed Thermal Properties on BWR Vessel Lower Head Failure and Timing," 15th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH 15, May 12 to 17, 2013, Pisa, Italy, Paper 500.

Pages 36 - 39: It is strongly recommended adding discussions of the works by Prof Nam Dinh and Prof Theofanous on IVMR in AP1000, specifically on different modifications of the ULPU facility.

Page 36: It would be appropriate to explain why the thickness of the metallic top layer is important for the focusing effect. You could use the energy splitting concept as it was discussed in the works of Theofanous.

Page 39: First paragraph of Section 1.3. It would be more adequate to state that IVMR has authors and it was not generally known before it was proposed, designed, justified using ROAAM methodology by Prof Theofanous and his coworkers and implemented at Loviisa NPP with quite extensive retrofit program (e.g. see reference [111]). Then, together with Prof Nam Dinh IVMR was justified for AP600 and AP1000. Their pioneering works motivated further IVMR related research in the world.

Page 39-40: "The calculation and experiments, proving the efficiency of external vessel cooling for lower power reactors, were demonstrated by the application of conservative assumptions. With such assumptions, heat removal at the vessel's outer wall cannot be guaranteed" This a contradictory statement. Heat removal is either demonstrated or cannot be guaranteed. It cannot be both.
With regards to the "conservative assumptions", it is strongly recommended to add references in the thesis to ROAAM methodology (e.g. the work of Theofanous "On the proper formulation of safety goals ..."), which was the key for justification and adoption of IVMR. ROAAM was much more comprehensive methodology than simply "conservative assumptions".

Page 40: "...phenomena that can influence the Lower Head of RPV failure." More appropriate wording would be: "...phenomena that can influence failure of the RPV Lower Head."

Page 40: "exemplary phenomena" is not correct wording to be used in this context.

Page 40: "The listed phenomena are not all of one, which was identified to highly influence the success of the IVMR strategy." Please, change the wording to clarify what you mean.

Page 43: "This is an extreme sequence because the reactor is equipped with multiple emergency power sources (redundant and diversified), so this scenario characterizes itself with low probability [56]" As it was demonstrated in Fukushima, such extreme sequences still can occur, especially in case of extreme external events. E.g. flooding (that will become more extreme with climate change) is capable of initiating failure of all (including backup) energy sources. Extreme droughts (especially for reactors cooled using water from rivers) can result in the loss ultimate heat sink.

Page 44: "The main aim of the tool is the performance of integral simulations for severe accidents of nuclear reactors (as also spent fuel pools), which can imitate physical phenomena". Using word "imitate" is not appropriate in this context.

Page 45: "Key analysis findings" Consider different wording. E.g. "Key findings from the analysis".

Page 45: "...where the coolant is not covering the fuel rod." It should be "rods".

Page 48: "The sources of PROCOR are developed in Java..." Wording should be revised e.g. "The source codes...".

Page 51: "Apart from this, the parameter influences the critical heat flux associated with debris bed coolability due to residual water presence in the lower head. The expression can be found in [54] taken from [70]." In the context of the debris bed coolability another term is commonly used, namely Dryout Heat Flux (DHF), see for instance works by S. Yakush et al. (2012). For the porosity range you can also refer to later work by Kudinov et al. (2010) The DEFOR-S experimental study of debris formation with corium simulant materials".

Page 51 - 52: "Critical Heat Flux (CHF) is computed with the ULPU correlation derived from the experimental campaign [71]" This statement is not correct. The authors of reference [71] did not carry out ULPU tests. See reference [28] in the work [71] for the origin of the ULPU experimental data for the CHF correlation.

Page 52: Figure 2.4 "no axial draining" and "masive draining".
These models should be described in the thesis in order to understand their impact.

Page: 53 Figure 2.5
Comment 1: Please, explain how sampling was done to obtain the data.
Comment 2: What the color scale means?

Page 62: "The review shows that while using this correlation, the lateral heat flux increases when the thickness diminishes, leading to a focusing effect, which can create an unrealistic overestimation of the vessel rupture evaluation for the IVMR strategy." The reason for the focusing effect is described by the "energy splitting", which is based on the energy conservation. All heat that is transferred from the melt pool to the metallic layer through the bottom surface of the layer in a steady state conditions has to be equal to the sum of heat released through the top surface (top heat) of metallic and the heat transferred to the wall through the lateral surface of the metallic layer (lateral heat). If thinning of the melt layer doesn't affect the top heat, then the same amount of lateral heat will be transferred through a smaller surface giving higher heat flux per unit area.

Page 63: "Previous studies [112], [113], [114], [115] with CFD tools were used to investigate natural convection problems, but they were not previously dedicated to the thin layers and specific reactor configurations." For completeness one should also references to the works of Chi-Thanh Tran, including "The Effective Convectivity Model for Simulation of Molten Metal Layer Heat Transfer in a Boiling Water Reactor Lower Head".

Pages 76, 77, Sections 4.5.2, 4.5.3.

1) It should be clarified that the approaches are valid only in case of constant thermal conductivity. It should be assessed how close thermal conductivity to a constant under the accident conditions.
2) For the quadratic profile model it should be noted that it doesn't describe situations when boundary conditions change during the transient.

Page 107: Subsection title "Stability analysis" does not reflect the model that is described in the section. More adequate would be "Surface deformation".

Page 111: "Crispation Number – Ga" it should be Cr instead of Ga.

Page 112: "When the thickness of the thin metallic layer becomes small $\Gamma = e L << 1$, the variation of vertical velocity and temperature are small. This implies that when the metallic layer heights are very thin, the convection cells will have lower chances of being established. This would lead to the heat transfer regime being shifted towards the conduction mode." This conclusion is not correct. For example, if we take an ocean (which can be considered as a layer of liquid), it will have very small Γ, yet no one would argue that heat transfer in the ocean is dominated by conduction. Convection vs thermal conduction (as in all other cases) is determined by the Re and Pr numbers, not aspect ratios of the domain.

Page115: "structure temperature (environment) temperature was Tstructure = 400 K." Selection of such low temperature of the reactor internals so far in the accident progression has to be justified.

Page 130: "Meshing and CFD setup used is at a good level of representatives of results – the inflation at the boundaries for the calculations is catching the temperature and velocity variations" Please check alternative wording for "representatives" and "inflation".

Page 137: "What is worth mentioning is that a decrease in heat flux results in a decrease in temperatures of the domain and probable mechanical load on the reactor pressure vessel wall." Please, clarify how heat flux is connected with the mechanical loads on the vessel wall.

Page 142: Figure 6.23. Why heat flux is shown as negative?

3 Comments requiring explanations

In this section we provide comments that require further clarification.

Comment 1:
Page 35. Discussion on the heavy metallic layer.
When speaking about heavy metal layer at the bottom it is important to clarify the assumptions about the origin of the heavy (U+Zr) metal that forms the layer. In the initial state, all fuel is made of uranium oxide UO_2. Cladding will be (at least partially) oxidized to ZrO_2. If UO_2 and ZrO_2 can interact with iron, then Fe oxides will be formed and metallic U and Z can be recovered. However, the configurations in which such reactions can occur and to which extent under prototypic accident conditions are actually not quite straightforward.
Also, one can expect at least some influence of the accident scenario, e.g., amount of water that would be injected in the vessel, e.g. in case of a delayed SBO scenario such as in Fukushima.

Thus, somewhat more extensive discussion on the uncertainties related to the formation and potential stability of the heavy metallic layer at the bottom of the melt pool would be appropriate.

Comment 2:
Page 51, Table 2.2 ,
Emissivity factor for lower and upper debris in lower head.
The reason for selecting the range of 0 – 0.5 has to be provided and the impact of possible wider range has to be discussed. E.g. the emissivity can be closer to 1 in case of heavily oxidized surface.

Debris bed porosity
It has been shown that with both prototypic corium melt and with melt simulant materials porosity of the debris bed can reach to quite high values, up to ~60-70%, (e.g. see Kudinov et al. (2010) The DEFOR-S experimental study of debris formation with corium simulant materials). Potential impact of further expanding the range for porosity should be discussed.

Page 52: "…is multiplied by fφ selected in the manner so that the maximum CHF is about 3 MW/m2". The maximum value of CHF is quite high and requires some justification. Also what was the lowest value of CHF? How changes in the range would affect the results?

Comment 3:
Page 54: "For these specific calculations, it was concluded that the model used in the calculations overestimates the lateral heat flux for a very thin layer." How was this conclusion reached? An explicit explanation is necessary.

Comment 4:
Page 54: "The correlations used for the heat transfer in the thin metallic layer are questionable for layer thickness below 10 cm and do not take into account the time delay for the establishment of natural convection." What is the origin of this statement? Is it from this work or from other studies, please, clarify.

Comment 5:
Page 61: "The simultaneous existence of Rayleigh–Bénard convection and Bénard–Marangoni convection is predicted to take place in the thin metallic layer and needs to be taken into account when making the evaluations of the heat flux on the lateral RPV wall." A justification for such a conclusion valid under accident conditions is needed at this point in the thesis. Such justification has to be based on some analysis. Otherwise, it should be presented as a hypothesis that should be tested.

Comment 6:
Page 62: "stationary evaluations cannot be considered as bounding with respect to the focusing effect during the transient formation of a metallic layer on top of the oxide pool, while the correlations were derived for stationary states [106]"
It is important to consider that for the vessel failure it is not sufficient to exceed critical heat flux in a transient process of formation of metallic layer. It is necessary to melt ablate the wall of the vessel such that remaining thickness of the wall (about 2-3 cm typically for IVMR from initial thickness of ~15 cm) is not capable of holding the weight of the vessel lower head and the debris bed in it. Such ablation takes time during which metal is supplied to the metal layer (also from the ablated vessel wall) that increases thickness of the layer. While it is true that

correlations are derived in steady state conditions, can we justify the conclusion that consideration of steady configurations are inapplicable as "bounding" for safety analysis?

Comment 7:
Page 65L Momentum and energy conservation equations assume that properties of the liquid (such as liquid phase thermal expansion coefficient, viscosity and thermal conductivity) are constants. How this assumption can be justified for the accident conditions with the phase change phenomena?

Comment 8:
Page 72, Figure 4.3: Can you explain how conservation laws are enforced in the process of the "mesh update"?

Comment 9:
Page 74: "BC = water_cooled, which implies the presence of the water on the top of the solid layer. The calculation of the 1D slab heat conduction will be performed by the defined (fixed) temperature on the top (right BC). The temperature for the right boundary will be set to water saturation temperature." In which situation such boundary conditions (that metal surface temperature is equal to coolant saturation temperature) are applicable and when such conditions are not applicable? A more detailed discussion is needed.

Comment 10:
Page 75: radiation heat flux boundary conditions. How the ambient temperature (T_inf) is determined? How it can affect the results of the simulations?

Comment 11:
Page 112-113: "The Marangoni number Ma becomes small when $\Gamma \ll 1$ (e.g., $e \ll L$), so that the thermal gradient at the surface has to be large – the term in the parenthesis on the right hand side of Eq. 5.51. This condition of thermal gradient presence at the surface will, in consequence, lead to fluid motion. Marangoni effects will modify the motion at the free surface and play a role in the flow regime for small thicknesses. It will be done by modifying the top heat exchange through velocity and thermal gradient."
From the text above, it seems that aspect ratio $\Gamma \ll 1$ is a sufficient condition for the strength of the Marangoni effects. However, one can imagine a case when depth of a liquid layer is large (e.g. ~1m), but the lateral extent is even larger e.g. ~1000m. Obviously $\Gamma \ll 1$ for such a layer. The question is: will Marangoni effect will be as strong in this configuration as in a case when the thickness of the liquid layer is just a few millimeters? If not, then what is the necessary condition for the assessment of the importance of the Marangoni effects on the convection?

Comment 12:
Section 5.1.4: While non-dimesionalization of the equations and then in-depth scaling analysis presented in the thesis are quite useful, it is not clear from the discussion what is the effect of turbulence on the heat transfer? How some of the conclusions presented in this section can be affected if flow regime is turbulent or laminar?

Comment 13:
Page 115: "The simulations were performed for stationary state with prescribed geometry of cylinder with radius fixed to R = 2 m and varying thickness in the range e = [0, 005; 0, 15] m." From a practical perspective, how a 30 mm thick metal layer can be formed on top of a debris bed? How to achieve flatness of the top surface of the debris bed withing 30 mm precision? If

we are considering that the bed is in a molten state and therefore its top surface is flat, then is it realistic to expect that during the time that is needed to remelt oxidic debris there will be only such small amount of metal accumulated at the top surface of the liquid oxidic bed?

Comment 14:
Page 123: "Around 540 W was transferred to the lateral wall for cellular flow, while about 480 W was for monocellular one, which gives around 10% difference."
Given the uncertainty in the CHF, how important is uncertainty of 10% in the heat flux from the metal layer, from the perspective of a safety assessment?

Comment 15:
Page 148, Figure 6.27: Why no near wall mesh refinement was used for the simulations? What can be an impact of the mesh refinement?

Comment 16:
Pages 161-162, Figures 6.42, 6.43: The different fitting formulas are proposed for different melt layer thickness (below 5cm and above 10cm). Would it be possible to use a non-dimensional criterion to distinguish between different correlations (e.g. that would be applicable to other low Pr luiquids)? It would be also valuable to compare obtained results with the prediction of exiting empirical correlations.

4 Summary

The topic and phenomena addressed in the thesis are quite challenging and obtained results are new and interesting from scientific and technical application perspectives. The PhD candidate has acquired high quality knowledge, competences and skills as an independent researcher that can plan and develop approach to solving scientific problems, carry out analysis, and evaluate obtained results.

Based on the review, if the comments above are properly addressed, I would suggest giving an "Outstanding" grade for the thesis.

I confirm that the doctoral dissertation of Eleonora Skrzypek, M.Sc. Eng. meets the requirements set out in Art. 186 paragraph l point 5 (Act of 20 July 2018 - Law on Higher Education and Science) and I am applying for admission of the PhD Candidate to the next steps of the doctoral procedure.

Sincerely yours,

Pavel Kudinov

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Royal Institute of Technology (KTH)