Appendix A

Contract AFT/NKS-R(18)122/4

Status Report

Scenarios and Phenomena Affecting Risk of Containment Failure and Release Characteristics

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1. Introduction

The goal of this project is to produce new data, and to develop models and methodologies for addressing severe accident scenarios and phenomena which are important to assess the risk of containment failure and radioactivity release in a postulated severe accident of Nordic nuclear power plants. The experimental studies and deterministic modelling at KTH and VTT provide necessary insights and data for scenarios definition and tools development which are important to PSA studies at LRC. Therefore, this joint research project enables the three Nordic partners to leverage their ongoing projects, so as to maximize the research outcomes and spread the excellences to each other. The collaborative project also helps establish/enhance the informal Nordic networks for information exchange on severe accident research.

The project has the following four work packages proposed in the activity plan:
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WP1: Experimental study of severe accident phenomena and modeling development for assessment of core melt risk and corium stabilization in a Nordic BWR.

- 1.1 In-vessel debris/molten pool behavior and RPV failure, in order to gain insights into complex in-vessel phenomena, including remelting of a debris bed to a molten pool, heat and mass transfer to the vessel wall and penetrations, failure of RPV penetrations (e.g., CRGTs, IGTs), and melt release scenarios including breach ablation/clogging issues.
- 1.2 Ex-vessel debris bed coolability, in order to produce new data to address the following critical issues: post dry-out heat and mass transfer of a debris bed, and corium oxidation and debris remelting.
- 1.3 FCI and steam explosion, involving large and small scale experiments to study molten fuel coolant interactions (FCI), using various oxides mixture and metal compositions to address material effects on melt fragmentation and its improvement, Zircaloy and steel oxidation and hydrogen generation, and triggered and spontaneous steam explosion and its suppression.
- 1.4 Modelling development for deterministic analysis .
- 1.5 Further development and application of ROAAM+ framework

WP2: Development of methods for coupling of Integrated Deterministic Probabilistic Safety Analysis tools such as ROAAM+ developed by KTH with PSA in general and PSA-L2 in particular.

- 2.1 Development of IDPSA generated data processing techniques for informing PSA about importance of (i) timing of events and (ii) epistemic uncertainty.
- 2.2 Different approaches will be considered in collaboration with KTH and VTT to addressing of dynamic events and physical phenomena in (i) cut sets; (ii) success and failure paths; (iii) connections to PSA-L3.

WP3: Deterministic modelling of debris bed coolability and threats for the containment integrity including steam and hydrogen explosions.

- 3.1 Establishing a temperature-based coolability criteria for debris beds to evaluate the coolability of a multi-dimensionally flooded conical debris bed less conservatively. Assessing more thoroughly the effect of heat transfer models to the evolution of temperature in time. Modelling a truncated cone case with MEWA. Comparing results with the DECOSIM analyses done by KTH. This task is performed in close collaboration with task 1.2 to find out the origin of the differences in the debris bed post-dryout temperature behavior noticed in previous analyses by VTT and KTH.

3.2 MELCOR analyses on hydrogen explosions. Examining accident scenarios that may lead to hydrogen explosions in the Nordic BWR containment and reactor hall.

3.3 MC3D analysis on the effect of vessel breaking mode to dynamic pressure loads on cavity wall induced by steam explosion. Assessing steam explosion loads in Nordic BWR geometry and examining the sensitivity of the results to key input parameters. Also assessing the effect of break location.

WP4: Level 2 PSA modelling of phenomena and factors affecting containment failure probability and release characteristics.

4.1 PSA-L2 analysis with the focus on the factors affecting source term characteristics. The factors to be considered are: (i) plant damage states (from PSA level 1), (ii) plant design and (iii) accident progression phenomena. Generic BWR model utilizing dynamic containment event trees is developed further, with special consideration of uncertainties.

4.2 Consideration of the factors affecting the probability and magnitude of relevant phenomena such as (i) steam explosions and (ii) non-coolable debris bed formation and core-concrete interaction. The results of KTH and LR, especially those represented in report NKS-395, will be utilized.

2. Progress and status

<u>WP1: Experimental study of severe accident phenomena and modeling development for assessment of core melt risk and corium stabilization in a Nordic BWR</u>

The REMCOD facility is developed with the aim of filling the knowledge gap in remelting phenomena of the debris beds. Based on the obtained results from previous tests (21 tests in total), the road map of the future research has been drawn by improvement of the follows:

- improved parametric study;
- facility design;
- experimental procedure; and
- measurement techniques.

So far, three types of experiments have been conducted:

- Melt penetration into cold debris (E1-E8)
- Melt infiltration through hot debris (E9 & E11)
- Remelting of initially solidified melt (E10)

A test matrix has been designed to resolve remaining issues associated with the remelting phenomena in the existing facility which includes test series E12, E13 and E14 (each test is composed of 4 subtests).

Post-processing of the experimental results has revealed interesting observations (see Fig. 1). Two flow regimes are identified in the melt infiltration process which is dominated at the beginning by capillary forces and Later it is governed by gravity forces. At the current state, scaling rules of the problem are identified for correlating length scales and time scales of infiltration process. Further simulation activities are in process for better understanding of competition mechanism between hydrodynamics and solidification.

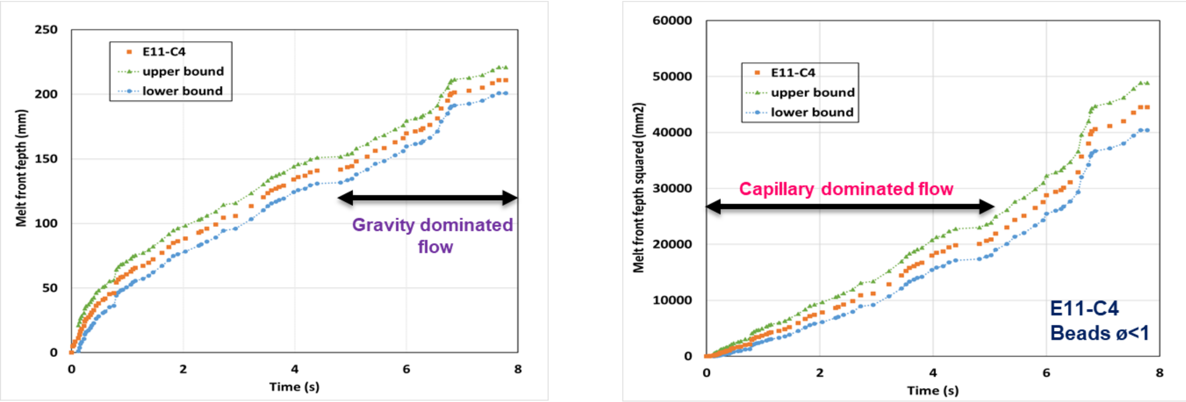

Fig. 1: Infiltration process of test E11.

Debris bed coolability is important to terminate and stabilize a hypothetical nuclear severe accident. Previously the POMECO-HT facility was developed at KTH to study long-term coolability of debris bed of various prototypical characteristics, with focus on measurement of dryout heat flux.

However, prior to the long-term collability (steady-state), a debris bed formed during fuel coolant interactions (FCI) must experience a quenching process (transient) which brings post-dryout debris bed to coolable state. In order to invetigate such quenching process, a new test facility called POMECO-Q is being considered at KTH, which is intended to address the quenching and post-dryout heat transfer of debris bed. The test section will be (2D) sliced geometry of rectangular cross-section, to simulate the ex-vessel conditions in two dimensions on an intermediate scale. The preliminary specifications of the experimental setup are as follows:

- power capacity: 84 kW;
- test section dimensions: ~600×12×500 mm^3;
- temperature up to: 800°C;
- water supply: top and bottom.

Currently, the experimental facility POMECO-Q is in its early design phase, and the progress will be done in various stages as follows:

- complete facility design and manufacture;
- conduct dryout experiments;
- go to higher temperatures and create post-dryout conditions;
- conduct the quenching tests;
- analytical development to represent the quenching and post-dryout heat transfer mechanisms.

MISTEE-HT facility at KTH is developed to conduct FCI experiments at high melt temperatures (T_{melt}>2000°C) with or without steam explosion triggering. The upgraded facility offers unique advantage to investigate the longstanding issues of so-called "material effect" in steam explosion and oxidation of metal melts during FCI. Recently the MISTEE-HT facility was successfully adapted to study thermal fragmentation characteristics of single droplets of Al_2O_3 (T_{melt}: 2054°C). Oxidation is the most uncertain part of understanding and modelling of fuel-coolant interaction studies. Experimental data on oxidation behavior during FCI is rather scarce and inconclusive. Hence, the focus of MISTEE-HT experiments is currently placed on the investigation of the chemical augmentation of Zr melt or a mixture of Zr and Fe melt under FCI conditions. The aim of the current work is to advance our current state of understanding on zirconium melt oxidation behavior as well as to provide conservative estimates on O/Zr ratio during the pre-mixing phase of FCI. In the experiments, interaction between the melt and water are recorded visually at high speed. Scanning Electron Microscopy (SEM) combined with Energy-Dispersive X-Ray Spectroscopy (EDS) were used to study distribution of phases and their composition. The investigation reveals complex radial stratification of oxygen content in the samples from the surface to the bulk of the droplet. Further, it is also found that the oxygen content increases at a decreased degree of water subcooling (cf. Fig. 2). Considering the scarcity of experimental data, the conservative estimates at varied experimental conditions are vital for model development. Experiments with a mixture of Zr and Fe melt are underway with adequate modification of materials used in the furnace.

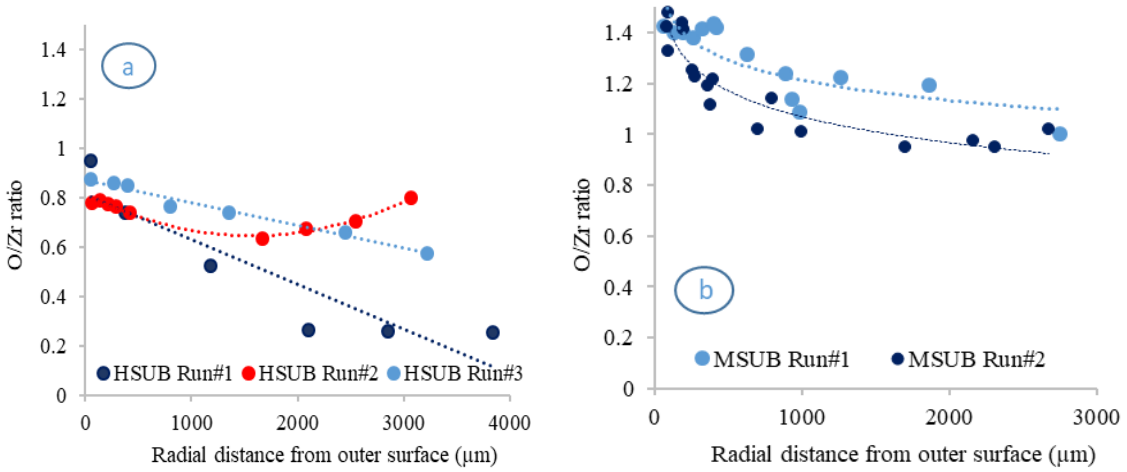

Fig. 2: Measured O/Zr ratio in the quenched samples under (a) high subcooling (ΔT_{sub}: 85K; HSUB series), *and (b) medium subcooling* (ΔT_{sub}: 45K; MSUB series).

SIMECO-2 facility is being developed to investigate heat transfer in 2- and 3-layered stratified molten pool formed by oxide and metal simulants with different densities covering the following key phenomena:

(i) redistribution (inversion) of oxide and metal simulants layers due to change of material densities
(ii) effect of the crust formation on the top/bottom layer interface
(iii) influence of top metallic layer thickness on the focusing effect
(iv) multidimensional heat transfer in, and between, the melt pool, the top metallic layer and the vessel.

The SIMECO-2 test section is developing as a slice-type vessel, which includes a semi-circular section, representing the lower head of the reactor vessel. Fig. 1 presents the general view of the SIMECO-2 test section. The diameter, height, and width of the working volume of pool are 1000×500×120 mm, respectively. One of the main feature of SIMECO-2 facility is optically transparent front and back walls made of quartz, that allows to have visual observation of pool behavior, such as crust growing and to measure velocities of local and global heat flows.

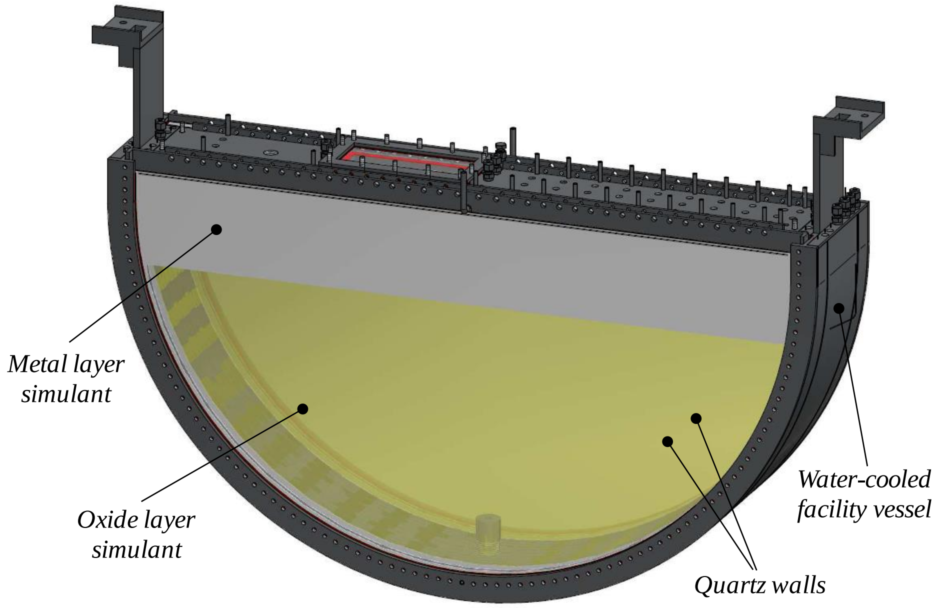

Fig. 3: The general view of the SIMECO-2 test section.

The planning experiments with high temperature molten salt (as oxide simulant) will be covered a temperature range up to 900 °C and internal Rayleigh numbers about $4 \cdot 10^{14}$. Variation of top metal layer thickness from 2 to 10 cm allows to investigate the focusing effect in the range of the concentration factor (ratio of heat flux to the wall and heat flux from the oxide layer) from 3 to 7 and covering external Rayleigh numbers about 6×10^6.

Current activity of SIMECO-2 development focuses on the test section construction and preparation of infrastructures including cooling system, melt preparation system, etc.

In the severe accident mitigation strategy for Nordic BWRs, vessel failure mode (including characteristic time of melt release, rupture size and location, and amount and superheat of melt available for release) and location would essentially affect melt-coolant interaction and debris bed coolability in the reactor cavity. The latest progress of computational power could allow more detailed modelling of reactor vessel failure, which could help understanding the relevant phenomena and predicting the accident progression more accurately. To explore such advanced computational capability, KTH is investigating the interaction between the corium and vessel by simulating the FOREVER experiment with a two-way coupling thermo-mechanical approach.

Currently the FOREVER-EC2 test is chosen to be simulated. A literature review was done on this test, the advances of reactor vessel failure simulations and general Fluid-Structure Interaction approaches. Inputs of all materials for both fluid solver and structure solver have been established. A one-way simulation was done for a case checking and to eliminate possible setting errors. Satisfactory results were obtained (2000 s discrepancy in predicting vessel failure time). Fig. 4 shows a temperature contour (left) when the temperature was stable and a creep strain contour (right) when the vessel failed. Two-way coupling would be explored soon after this simulation.

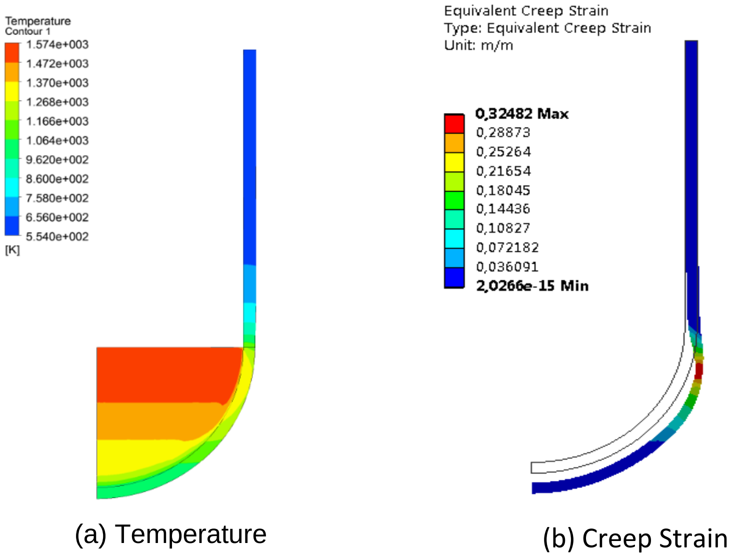

Fig. 4: Snapshots from the one-way coupling.

WP2: Development of methods for coupling of Integrated Deterministic Probabilistic Safety Analysis tools such as ROAAM+ developed by KTH with PSA in general and PSA-L2 in particular

The goal of WP2 is development of IDPSA generated data processing techniques for informing PSA about importance of (i) timing of events and (ii) epistemic uncertainty. The uncertainty analysis performed in last year´s report was a simplified approach. A more correct approach would be to study the uncertainties where they arise. It is in principle possible to, using the data used in the ROAAM+ approach, gather such information. It has however been found that the sampling of cases used in the ROAAM+ approach does not translate directly into uncertainty propagation through the modified containment event tree in Monte Carlo-analysis. LRC will therefore clarify in the report how the sampling is performed in RiskSpectrum PSA and how the unacceptable release frequency is calculated.

In particular, the correlation effect of different input parameters where there are "competing" phenomena for containment failure (e.g. steam explosion and debris coolability) will be discussed. It has been concluded that this issue cannot be directly solved in the current framework of ROAAM+ and standard PSA level 2 modeling. To solve this; KTH will on their side look into methods of addressing these correlations within the ROAAM+ framework and LRC will extend their current scope of studies for melt release diameter with a bounding pessimistic case, a sensitivity study and a bounding optimistic case.

Also, LRC will clarify the reasons for the large difference between IM isolation and loss of feedwater cases as well as implement a new grouping of sequences where the consequence "Basemat meltthrough" is grouped together with the previous unacceptable releases into a general category of non-contained release.

The pilot study will be updated with these refined data and extended calculations, to be able to evaluate their impact on the overall results of the PSA

WP3: Deterministic modelling of debris bed coolability and threats for the containment integrity including steam and hydrogen explosions

VTT is analyzing the evolution of debris bed temperature behaviour in post-dryout conditions is continued assessing the effect of heat transfer models to simulation results more thoroughly. MEWA and Fluent simulations have been performed for truncated-cone debris beds to exclude the complex physics in the cone tip. The shape of the beds and spatial discretization are the same as in the DECOSIM computations of KTH. The same three different particle sizes (1, 2 and 3 mm) were also used with various heating powers.

At VTT the Fluent implementation was verified further by applying the Tung & Dhir friction model and comparing simulation results to the MEWA results for the same friction model. The Fluent simulations were repeated with the Schmidt (2007) version of the modified Tung & Dhir model. In case of truncated-cone debris beds, the differences between Fluent and DECOSIM results show the same characteristics as obtained previously in the conical bed cases.

WP4: Level 2 PSA modelling of phenomena and factors affecting containment failure probability and release characteristics

The first draft of a report focusing on modelling of timings and uncertainty analysis in dynamic containment event trees has been written by VTT. A simple emergency core cooling system recovery case has been used to demonstrate different options to model the recovery time and the effects of different timings. Epistemic and aleatory uncertainties have been separated in the case study, and two-phase uncertainty analysis has been performed. A high pressure melting containment event tree from the previous year has also been developed further, e.g. by modelling timings explicitly.

3. Concluding remarks

This brief report provides the progress and status the project “Scenarios and Phenomena Affecting Risk of Containment Failure and Release Characteristics” (SPARC) being carried out by KTH, VTT and LRC. The focus of this project is to produce new data and to develop models and methodologies for addressing severe accident scenarios and phenomena which are important to assess the risk of containment failure and radioactivity release in postulated severe accidents of Nordic nuclear power plants. The main achievements obtained so far are as follows.

In general, the work plan of the research activity has been fulfilled by around 50%, with involvement and contributions of many researchers at KTH, VTT and LRC, including young students and engineers. The research efforts will be enhanced and spreading to the entire activity space during next 6 months.