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Ex-Vessel Coolability and Energetics of Steam Explosions in Nordic Light Water Reactors

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Abstract

The report summarizes activities conducted at the Division of Nuclear Power Safety, Royal Institute of Technology-Sweden (KTH-NPS) within the ExCoolSe project during the year 2005, which is a transition year for the KTH-NPS program. The ExCoolSe project supported by NKS contributes to the severe accident research at KTH-NPS concurrently supported by APRI, HSK and EU SARNET. The main objective in ExCoolSe project is to scrutinize research on risk-significant safety issues related to severe accident management (SAM) strategy adopted for Nordic BWR plants, namely the Ex-vessel Coolability and Energetic Steam explosion. The work aims to pave way toward building a tangible research framework to tackle these long-standing safety issues. Chapter 1 describes the project objectives and work description. Chapter 2 provides a critical assessment of research results obtained from several past programs at KTH. This includes review of key data, insights and implications from POMECO (Porous Media Coolability) program, COMECO (Corium Melt Coolability) program, SIMECO (Study of In-Vessel Melt Coolability) program, and MISTEE (Micro-Interactions in Steam Explosion Experiments) program. Chapter 3 discusses the rationale of the new research program focusing on the SAM issue resolution. The program emphasizes identification and qualification of physics-based limiting mechanisms for both in-vessel phenomena (melt progression and debris coolability in the lower head, vessel failure), and ex-vessel phenomena. Chapter 4 introduces research results from the newly established DEFOR (Debris Formation) program and the ongoing MISTEE program. The focus of DEFOR is fulfill an apparent gap in the contemporary knowledge of severe accidents, namely mechanisms which govern the debris bed formation and bed charatersitics. The later control the debris bed coolability. In the MISTEE program, methods for image synchronization and data processing were developed and tested, which enable processing of MISTEE data obtained with a high-speed Xray radiography and high-speed digital photography. Discussion of uncertainties and severe accident simulation code capability for prediction of the threats on containment integrity is given in Chapter 5.

Key words

LWR, Severe Accidents, Accident Management, Ex-Vessel Melt, Debris Coolability, Steam Explosion, Experiments

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Contents

Figures

Tables

Chapter 1
Introduction to the Ex-CoolSe Project

1.1 Severe Accidents Safety and Issues

The main safety goal of modern nuclear power plants is to ensure the public safety against radioactivity which may be released during reactor accidents. To achieve this goal the reactors have been designed with the defense-in-depth concept and built upon the design-based accidents (LOCA) which involves the loss of cooling due to the break of the main coolant pipelines. However, Three Mile Island 2 (TMI-2) accident [1] deepened a public concern of the accident progression further beyond the design-based accidents which lead to core meltdown. These beyond-the-design-basis accidents, i.e., severe accidents, clearly involve melting of the nuclear reactor core and release of radioactivity. Intensive research has been performed for years to evaluate the consequence of the postulated severe accidents. It is clear that maintenance of the integrity of reactor vessel and containment is a key to ensure the public safety against risk resulted from severe accidents.

Severe accidents posed, to the reactor researchers, a most interesting and most difficult set of phenomena to understand, and to predict the consequences, for the various scenarios that could be contemplated. The complexity of the interactions, occurring at such high temperatures (~2500ºC), between different materials, which are changing phases and undergoing chemical reactions, is simply indescribable with the accuracy that one may desire. Thus, it is a wise approach to pursue research on SA phenomena until the remaining uncertainty in the predicted consequence, or the residual risk, can be tolerated.

In the PRE-DELI-MELT project [2] at NKS, several critical issues on the core melt loadings in the BWR and PWR reactor containments were identified, and the comprehensive assessment of severe accident management schemes adopted currently in Nordic BWRs and PWRs was performed. Also the final report suggested the experimental research facilities in the Nordic countries which had potential to utilize to resolve the issues. The report emphasized that research efforts should focus on following severe accident management issues:

(a) Coolability of the melt pool or particulate debris.
(b) Energetics and debris characteristics of fuel-coolant interaction.
(c) Vessel failure.

Many of Nordic nuclear power plants, particularly in boiling water reactors, adopted the Severe Accident Management Strategy (SAMS) which employed the deep subcooled water pool in lower dry-well. The success of this SAMS largely depends on the issues of steam explosions and formation of debris bed and its coolability.

From the suggestions of the PRE-DELI-MELT project, a series of research plan was proposed to investigate the remaining issues specifically on the ex-vessel coolability of corium during severe accidents;

(a) ex-vessel coolability of the melt or particulate debris, and
(b) energetics and debris characteristics of fuel-coolant interactions endangering the integrity of the reactor containments.

In this report, the activities of the ExCoolSe project in 2005 will be summarized. During the year 2005, the main activities aim to scrutinize the most risk-significant safety issues of ex-vessel Coolability and steam explosions in the Nordic nuclear power plants, and to build a tangible research framework to tackle the issues. The work in the NKS-ExCoolSe project is complementary to the work in the APRI project and in this way the results are shared. The result showed in the report is to benefit a greater community of Nordic NKS from work carried out also under APRI funded by SKI and Swedish utilities.

The final repost consists of five chapters. The chapter 1 describes the project objectives and work description. In the chapter 2, critical assessment of research results obtained from the up-to-the present KTH activities. The chapter 3 expounds the rationale of new research approach toward to resolve both issues. New research results and progress on the new framework are described in the chapter 4. And the report is concluded in the chapter 5.

1.2 Project Description and Work Plan

The NKS-ExCoolSe project in year 2005 aims to investigate both fields; ex-vessel coolability and energetic fuel-coolant interactions. Two tasks were planned as (a) ex-vessel coolability of melt pool or particulate debris beds and (b) energetics and debris formation of steam explosion. The descriptions of two tasks are depicted in the following sections. The research results are summarized in the following chapters.

1.2.1 Task 1: Ex-vessel coolability of melt pool or particulate debris beds

We had conducted two sets of experimental programs with two facilities for research under this topic; and the modified POMECO (porous media coolability) facility [13, 14] and the COMECO (corium melt coolability) facility [21]. The emphasis in the previous research was on the enhancement of coolability of porous corium outside of the reactor vessel due to natural and “engineered” cooling mechanisms such as top, side, bottom flooding and downcomers respectively for both the particulate debris beds and the melt pools in the multi-dimensional aspects. In many of Nordic LWRs, the lower cavity flooding at adequate time of the progress of severe accidents is practiced as one of Severe Accident Management Strategy (SAMS) to prevent severe accident progression. However, it is still uncertain that the coolability of ex-vessel corium melt is ensured. Therefore the examination of potential of natural and engineered cooling mechanisms as a measure for ex-vessel melt coolability management is of essence.

In this project as a continuation of the previous ExCoolSe project [3] on coolability, we focus an in-depth analysis of thermal hydrodynamic processes in the existing POMECO and COMECO experimental results to determine relevance and applicability of the data for the assessment of debris coolability in prototypical reactor scenarios for Nordic power plants in particular. In this process, important phenomena where additional coolability experiments are critically required to reduce uncertainty in the assessment of SAMS success in Nordic power plants will be identified and tested in the previous POMECO facility [16, 17, 19] with minor modification. New POMECO experiment [13, 14, 15] will be prepared after a feasibility study to define and design such a "critical" coolability experiment and performed in this project period.

The task aimed to accomplish three milestones as below.

- **Milestone 1 (T1M1):** In-depth analysis of the existing POMECO and COMECO experimental database to determine relevance and applicability of the data for the assessment of debris coolability in prototypical reactor scenarios for Nordic power plants.

- **Milestone 2 (T1M2):** Identification of important phenomena where additional coolability experiments are critically required to reduce uncertainty in the assessment of SAMS success in Nordic power plants.

- **Milestone 3 (T1M3):** Modified POMECO debris coolability experiment
    - ✓ Modification of POMECO facility
    - ✓ Coolability tests for key thermal-hydraulic phenomena to assess the debris coolability in prototypical reactor scenarios for Nordic power plants

- **Milestone 4 (T1M4):** Assessment of debris coolability based on POMECO and COMECO database

1.2.2 Task 2: Energetics and Debris Formation of Steam Explosions

The work in this task is important for the Nordic LWR containments in which a deep-water pool is established as an accident management strategy. It is clear that if a relatively large steam explosion occurs near the bottom of the 7 to 11 meters pool; the Nordic LWR containment (in particular the pedestal) can fail. It is also clear that the existing experiments, so far, indicate that the conversion ratio (or energetic yield) in a triggered UO_2–ZrO_2 explosion is significantly less than that in a triggered Al_2O_3 or stainless steel melt explosion. There are some limiting mechanisms which reduce the yield for non-eutectic oxidic mixtures.

Since it is infeasible to perform large-scale steam explosion experiments with UO_2–ZrO_2 or UO_2–ZrO_2–Zr and it is very difficult to establish a scaling relationship, we believe that a more fundamental investigation will bear fruit in terms of identifying the explosion mechanisms. We have investigated this for the jet break-up phenomenon and the micro-interaction steam explosion experiments (MISTEE), wherein, currently, we are observing the differences between the character of the explosion phase of a steam explosion, for a single droplet melts. As experimental parameters, we vary the subcooling of water, trigger strength and the melt droplet superheat.

The information of melt debris formation during steam explosion will be of importance to determine the configuration (for instance, debris porosity) of melt debris inside or outside the vessel relocated during severe accidents. In this study, therefore, the formation of fragmented debris during the explosion and mixing phases of Fuel-Coolant Interaction will be examined by performing single drop and small-scale jet experiments with the visual observation and debris characterization.

Precise evaluation of energetics and debris formation during jet break-up process of steam explosions in single drop and small scale jet tests requires the transient local quantities such as explosion pressure, bubble dynamics and visual quantification of jet break-up. In so doing, a very fast pressure transducer and high-speed visualization were employed in the MISTEE facility [47]. At the same time, the MISTEE facility was recently improved with a new high-speed camera for the enhancement of X-ray radiography images. This new system called **SHARP** (**S**imultaneous **H**igh-Speed Image **A**cquisition by **R**adiography and **P**hotography) [52] allows to correlate the rapid heat transfer during FCIs quantified by pressure signals and high-speed photography images to melt break-up and fine fragmentation process simultaneously observed by high-speed X-ray radiography images which has never performed in previous research.

The collected data will be synthesized to identify the jet break-up and explosion mechanisms. This will provide fundamental clues of jet-break-up, triggering and explosion process of FCIs as well as basic data to construct the physical models or evaluate the pre-existing models of FCIs and associated debris formation.

Therefore in this project, two set of experiments will be conducted in this period; (a) continuation of single drop experiment and (b) new small-scale jet break-up experiment

The task aimed to accomplish three milestones as below.

- **Milestone 1 (T2M1)**
  Development of the SHARP system

- **Milestone 2 (T2M2)**
  Fine fragmentation and energetics of steam explosions using single drop tests with the SHARP visualization system

- **Milestone 3 (T2M3)**
  Construction of small scale jet break-up test facility

- **Milestone 4 (T2M4)**
  Melt jet breakup and debris formation using jet breakup tests with the SHARP visualization system

Chapter 2
Critical Assessment of Research Results

2.1 Coolability of Corium and Debris Beds

2.1.1 POMECO Program: A Study of Particulate Debris Bed Coolability

2.1.1.1 POMECO Experiments

The POMECO (**PO**rius **ME**dia **CO**olability) program [17] was initiated in 1998 and designed to study coolability of particulate debris beds, for both in-vessel and ex-vessel scenarios. The POMECO test facility is shown in Figure 1, consisting of two stainless steel tanks with the lower tank being the test section and the upper tank is used for water overlayer for top flooding purpose. Both have the same cross-section of 350 mm square. The test section has a height of 500 mm and the height of upper tank is about 900 mm. In the test section, a sand bed is used to simulate a corium debris bed. The heating provided in POMECO is close to the rate of decay heat generated in the corium in a severe accident scenario. The bed can be quenched from top by an overlying water pool, and from bottom by using downcomers. In addition, to study the effect of non-condensable gases generated during molten-corium-concrete interactions (MCCI), on the quenching process, air and argon can be injected from the bed's bottom.

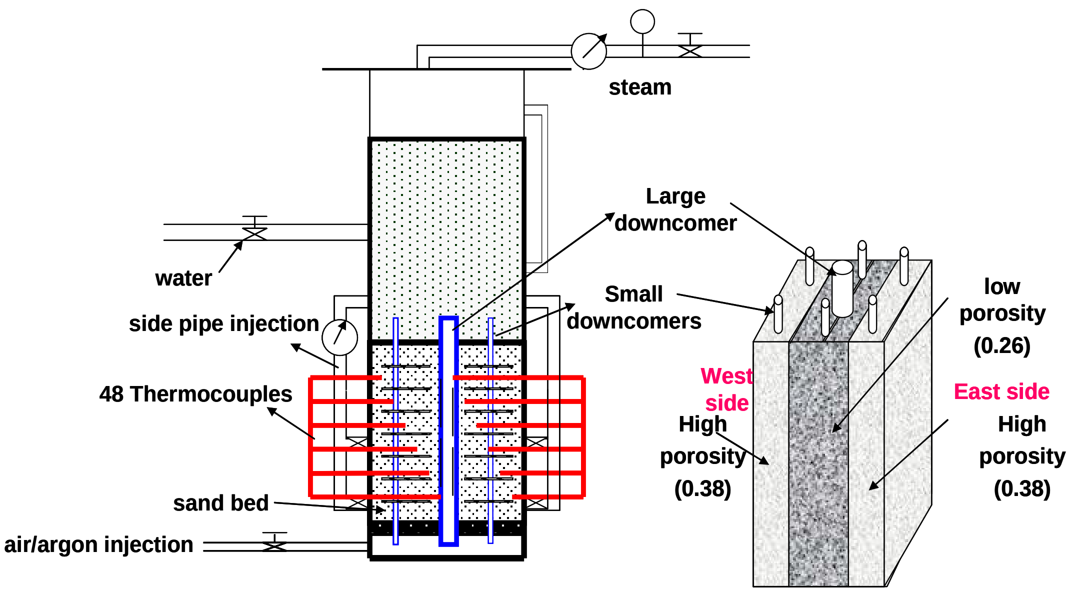


Figure 1. The schematic of POMECO test section (left) and a configuration of particulate bed with downcomers (right).

2.1.1.2 Research Activities

POMECO work [13, 14, 15]during this period was focused on a radially stratified debris layer, postulated to form ex-vessel when a corium jet breaks up a deep water pool. This configuration complements previous tests on POMECO with uniform beds and axially stratified debris beds.

The porous debris bed was simulated by using river sand particles with a specified size distribution. The selection of the particle size and bed porosity is guided by information about characteristics of corium debris as formed in prototypic corium experiments. In POMECO, three types of sand were employed (Table 1).

Table 1. Sand used for preparing the porous debris beds in POMECO .

Sand Sample	Size	Porosity	Mean particle size
A	2 ~ 5	0.41	4.0
B	0.5 ~ 2	0.38	0.9
C	0 ~ 2	0.40	0.2

A mass mixture of A, B and C with proportion 7:7:6 yielded a sand composition with porosity of 0.26 and mean particle size of about 0.8 mm. The radially stratified bed was prepared by putting the high porosity sand (B) with porosity of 0.38 at the periphery and the low porosity sand of porosity 0.26 at the centre of the bed as shown in Figure 1. The thickness of the low porosity layer was almost equal to the sum of those of the high porosity layers.

The bed was heated by employing thin electrical heaters with a capacity of 46 kW which corresponds to the volumetric power of 0.834 MW/m^3. This heat generation rate is nearly the estimated decay heat rate for the corium mixture. In the test section, 24 heaters (having diameter 6 mm, material Inconel) were used to heat the sand bed. A uniform spacing between the heaters was used (radial and axial distances between columns and rows are 25 mm and 35 mm, respectively).

For measurement, 48 K-type thermocouples were located symmetrically half on either side of the bed (8 different radial planes and 6 axial planes at a given radial plane). Thus, thermocouples are split equally between the low porosity and high porosity regions.

Seven downcomers were placed in the test section to bring water from the top tank to the bottom of the bed for bottom flooding purpose. The centre downcomer had a larger size, with inner diameter of about 54 mm, as compared to the others. The smaller downcomers had an inner diameter of about 9.5 mm and they were placed at the bed’s periphery as shown in Figure 1.

2.1.1.3 Results, Lessons Learnt and Recommendations

Results and lessons learnt from the POMECO debris bed coolability experiments and analysis and further recommendation are as below:

- In POMECO tests with radially stratified beds, it was observed that the quenching rate with top flooding alone was very small.

- With bottom gas injection, counter-current flow limitation (CCFL) conditions further limit the bed's quenching. Due to the side cooling resulting from higher porosity, water ingression at the bed's periphery reduces the quenching period.

- In POMECO tests with the downcomers, the bottom flooding (in addition to the top flooding) significantly reduces the quenching time. The quenching period is found to be affected by the location and the size of the downcomers. As expected, quenching rate in the low porosity layer is lower than that in the high porosity layer.

- The above POMECO test results suggested that bottom coolant injection is a must-go avenue, as opposed to the previous strategy that relies on top flooding alone. The work in APRI-5 led to the formulation of a new concept, named Natural Circulation-cooled Debris Catcher (NCDC). The NCDC utilizes the bed's heating power to engine two-phase natural circulation through the porous bed, hence providing an effective cooling even for large, deep corium beds. Further study of two-phase thermal hydraulics in porous media is recommended, including a mechanistic, multi-dimensional analysis of the POMECO tests with downcomers.

- The POMECO tests were also conducted with a pipe in the test section, that represents the cooling effect of control rod guide tubes (CRGT) in the BWR lower plenum. The test result indicates that CRGT cooling system provides additional cooling capacity for the particulate debris bed through an enhancement of the dryout heat flux and the quenching rate. Heat removal rate through CRGT was determined in the range of 10-15 kW per tube for the bed's composition and temperature regimes tested. More mechanistic analyses of the CRGT effect, and perhaps additional experiments, are highly recommended to help solidify the assessment of the CRGT effect on in-vessel debris coolability and possible retention in certain severe accident scenarios.

2.1.2 COMECO Program: A Study of Corium Melt Coolability

2.1.2.1 COMECO Experiments

The COMECO (**CO**rium **ME**lt **CO**olability) program [20-24] was designed to study coolability both for in-vessel and ex-vessel situations. The COMECO facility as shown in Figure 2 consists of a test section (200 x 200 mm) with a height of 300 mm. During the COMECO test, about 14 liters of binary oxidic melt were poured into the test section, which is heated by four heaters located outside the test section. The heat generation rate is at the corium's decay heat level in selected scenarios under consideration. The melt was then flooded by water from above. The depth of water pool was kept constant at around 700 mm throughout the experiments. The transient temperature behavior in the melt pool at different axial and radial locations was measured with 24 K-type thermocouples and the steam flow rate was measured using a vortex flow meter.

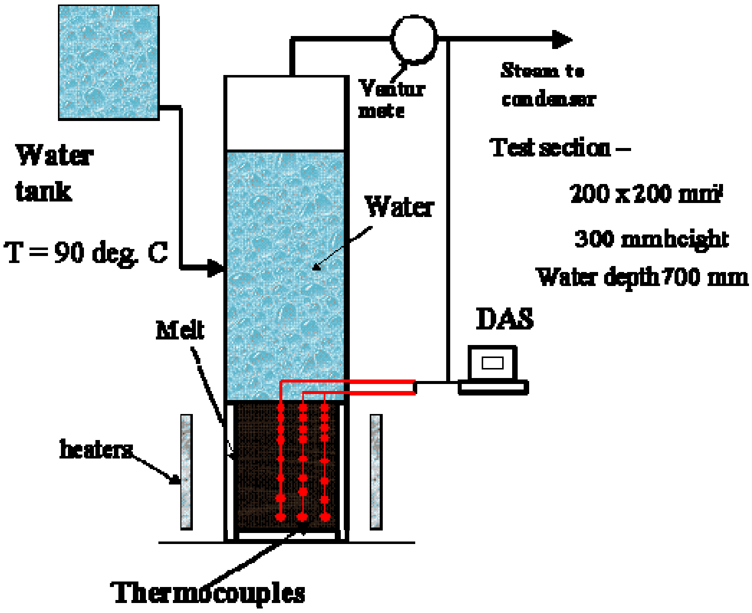


Figure 2. The schematic of COMECO facility

2.1.2.2 Research Activities

The COMECO tests [21] were performed with top flooding, with and without gas injection from the bottom (to study the effect of gaseous products from concrete decomposition), with and without "downcomers" (to study their effectiveness in enhancing debris coolability).

Two binary oxide mixtures were used in the COMECO test series: 30 % CaO+70 % B_2O_3 (by weight) and $MnO+TiO_2$ melt. Only the tests with CaO-B_2O_3 mixture were successfully completed. The tests with $MnO+TiO_2$ mixture failed due to the limitation of the existing furnace and crucible technology in working with a high-melting-point oxidic mixture.

Figure 3. Structure of debris upper layer from COMECO top-flooding tests.

2.1.2.3 Results, Lessons Learnt and Recommendations

Results and lessons learnt from the COMECO corium bed coolability experiments and analysis and further recommendation are as below:

- The COMECO results generally exhibit a similar quenching pattern as observed in similar top-flooding experiments such as in MCCI and FOREVER programs.

- Water ingression was limited to a shallow depth as determined by the temperature distribution in the melt pool at different axial locations. A major portion of the melt pool could not be quenched even with heat transfer from the melt to the water overlayer (Figure 3).

- The COMECO test with gas injection from bottom shows a strong effect of the injected gas flow on the quenching rate.

- The COMECO tests conducted with a downcomer inside the melt pool show the reduced quenching time, as the downcomer channels water to the pool bottom, hence facilitating “bottom cooling”. This bottom cooling was found to dominate the melt cooling process. However, the effect of the downcomer was not as significant as expected. The expectation was based on the effect of downcomers on coolability of particulate debris beds tested in POMECO facility.

- Additional testing with COMECO facility is not recommended in light of data available on the subject and ongoing work in OECD MCCI program, that APRI participates in.

2.1.3 SIMECO Program: A Study of Stratified Corium Pool Heat Transfer

2.1.3.1 SIMECO Experiments

The SIMECO (**SI**mulation of **ME**lt **CO**olability) program [25-31] at KTH was started in 1997, to aid the understanding, modeling and numerical simulations of natural convection heat transfer in a homogeneous pool and stratified pool, representing molten metal layer above an oxidic corium pool in the vessel lower head during a severe accident.

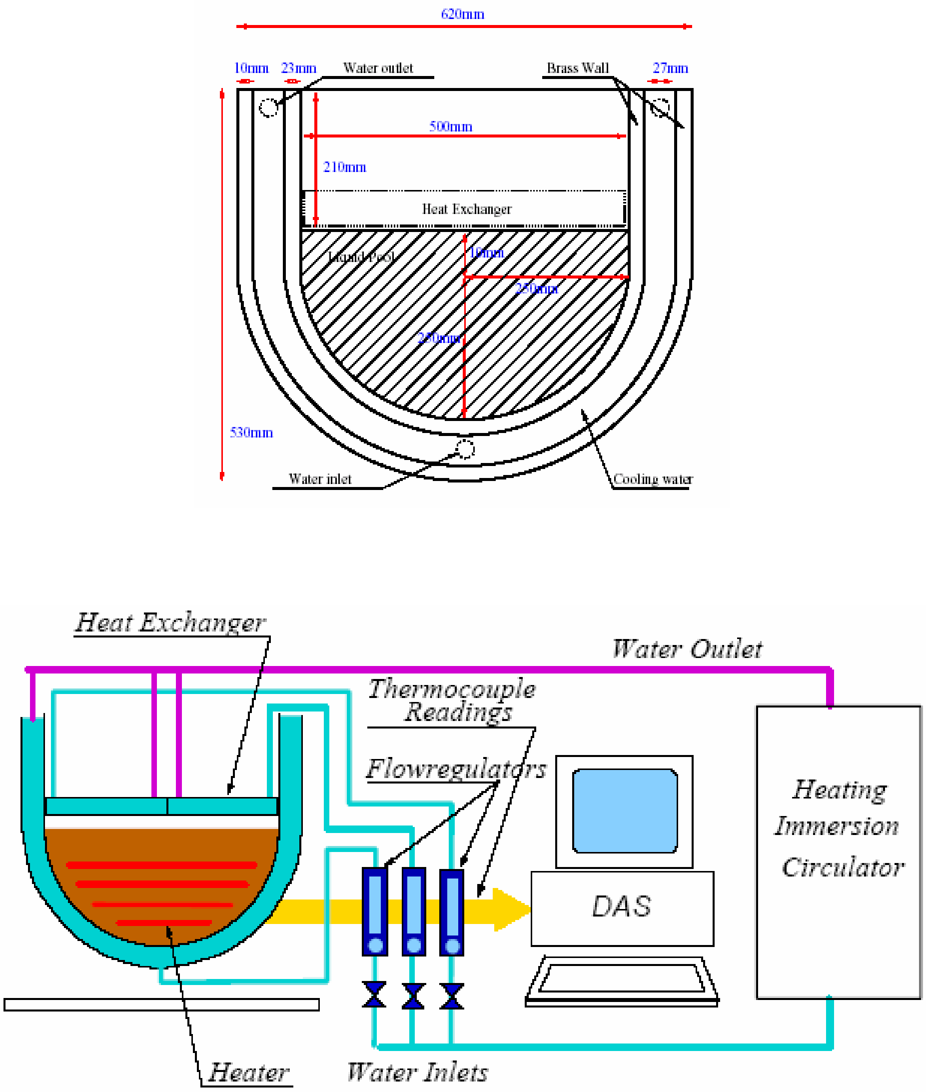


Figure 4. The schematic of the SIMECO test section and test facility.

The SIMECO facility as shown in Figure 4 consists of a slice type vessel, which includes a semi-circular section and a small vertical section, representing the lower head of the reactor vessel. The size of the facility is scaled to be 1/8 of prototype PWR type reactors. The vessel's sidewall represented by a thick brass plate, is cooled by a regulated water loop. Top of the vessel is cooled to provide isothermal conditions. The sideways and downward heat fluxes are measured by employing arrays of thermocouples at several different angular positions.

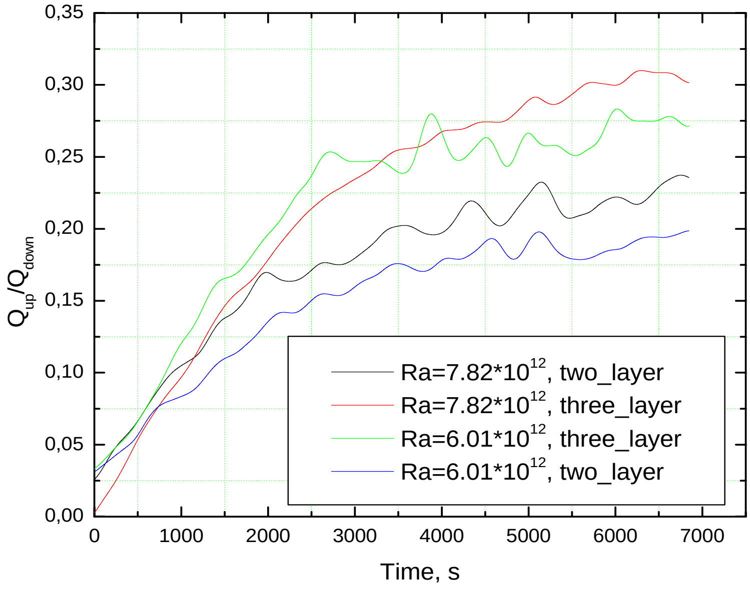


Figure 5. Q_{up}/Q_{down} ratio in SIMECO two- and three-layers experiments.

2.1.3.2 Research Activities

During the period, the SIMECO work [25] aims to study and characterize the natural convection heat transfer behavior in a three-layer stratified pool as observed in the MASCA project. Experiments were conducted with three stratified layers of immiscible fluids simulating the molten corium for various heat generation rates in the pool, while keeping the depth of pool constant. The simulants chosen were chlorobenzene, water and paraffin oil, which simulate the U-Fe metallic melt, melt containing the oxides of (U-Zr) and Fe-Zr metallic melt respectively. The pool was heated by a coil type immersion heater, with spatially uniform heat generation rate. The pool was cooled from side and top by water keeping its flow rate and inlet temperature constant so as to provide isothermal boundary conditions.

The heat transfer behavior of the pool was investigated for five different conditions, i.e. (i) when the middle layer and partial top layer generate heat, but the bottom layer do not generate any heat, (ii) when the middle layer only generates heat and the other two layers does not generate any heat, (iii) when the middle layer and partial bottom layer generate heat and the top layer does not generate any heat, (iv) when the heat generating bottom layer is extended and heat generating middle layer is squeezed so all 3 layers receive heat, and case (v) when the heat is generated only in the top two layers and the top layer is extended compared to the case (i).

The main idea behind this study was to compare the heat transfer behavior and thermal load on the vessel wall for these five conditions. The upward and downward heat fluxes, along with their ratio, were calculated and compared. The angular distribution of the heat flux on the side wall was determined and compared.

2.1.3.3 Results, Lessons Learnt and Recommendations

The new SIMECO results are useful for understanding the convection characteristics inside the stratified pool and determination of the heat load on the reactor vessel. In particular, we learn that

- In all the cases, the interface resistance between the stratified heated layers was found to affect the upward convective heat transfer rate (Figure 5). This interface resistance was found to be the strongest in the case (iii) when the top and bottom layers were both unheated and middle layer was only generating heat. Q_{up}/Q_{down} ratio was the lowest for this case (iii).

- The heat flux distribution in the vessel wall is found to be similar in all the five cases. However, the magnitude of peak heat flux is found to be larger for case (v) and smallest for cases (iii) and (iv). This implies that presence of trace amount of heat generating fission products in the bottom layer can reduce the peak heat load.

- The upward to downward heat flux ratio is found to be around 0.3 and has a small variation with Rayleigh number or difference in heating conditions in the pool.

To ensure the applicability of SIMECO findings to reactor scenarios, it is recommended to use detail numerical (CFD) analyses to evaluate the significance of non-prototypic fluid Prandtl numbers, Raleigh number and heating method in the SIMECO tests. This work will complement the validation of lower head module in the ASTEC code on SIMECO results – an activity to be performed in collaboration with CEA and IRSN under the SARNET program.

2.1.4 FOREVER Program: A Study of In-Vessel Coolability and Vessel Failure

2.1.4.1 FOREVER Experiments

The FOREVER (**F**ailure **O**f **RE**actor **VE**ssel **R**etention) program [32-42] at KTH was started in 1997. The first FOREVER test was conducted in 1998. Since then a number of tests was conducted and the program remains one-of-a-kind (with both melt and decay heat simulation), which contributes to the state of the art in severe accident analysis.

These experiments are simulating the behavior of the lower head of the RPV under the thermal loads of a convecting melt pool with decay heating, and under the pressure loads that the vessel may suffer in a depressurization scenario. The geometrical scale of the experiments (Figure 6) is 1:10 compared with a prototypic LWR. The experiments are scaled 1/1 for vessel wall temperatures, pool heat flux and its polar distribution. A scaling distortion is in the low value of the temperature drop across the vessel wall, since the wall thickness of the experimental vessel is 1/10th of the prototypic value. The experiments reproduce the prototypic melt pool convection process and the temperature field in the vessel wall. A substantial database on combined natural convection-induced thermal loads and multi-axial creep deformation of a 1:10 scale vessel under prototypic conditions was obtained.

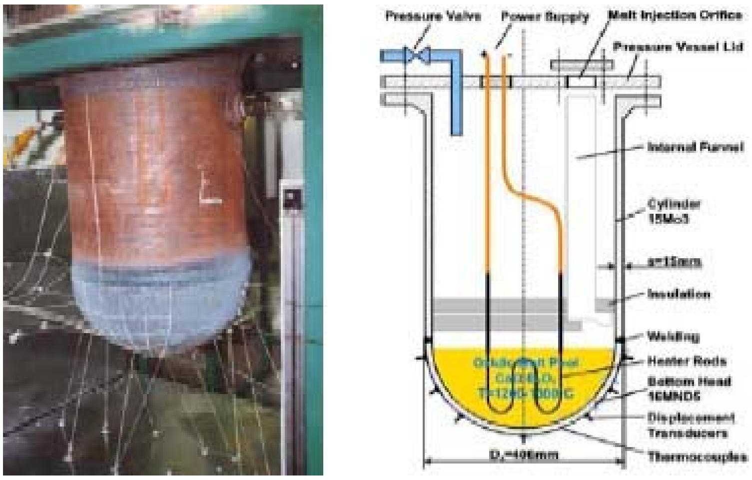


Figure 6. The FOREVER facility: a 1/10th scale (400mm diameter, 15mm wall thickness) carbon steel vessel, constructed, welded, and heat-treated according to the vessel manufacture code. The experiment is performed by pouring a binary oxide (CaO-B_2O_3) melt of about 12 liters at 1200°C into a scaled reactor pressure vessel, heating the melt to maintain temperature level at 1100 to 1200°C, and pressurizing the vessel wall up to 25 bars pressure with Argon gas. The vessel wall temperature reached 800 to 1000° and the vessel experienced creep and eventually failure.

In addition, the EC-FOREVER experimental program considered the accident management action of restoring the water supply to the vessel, where the melt could be cooled and the vessel thermal loading relieved to prevent the vessel failure. In this context, FOREVER-EC5 and FOREVER-EC6 experiments were conducted to study in-vessel coolability of melt pool by top flooding, and the effectiveness of gap cooling by supplying water atop the melt pool in the vessel.

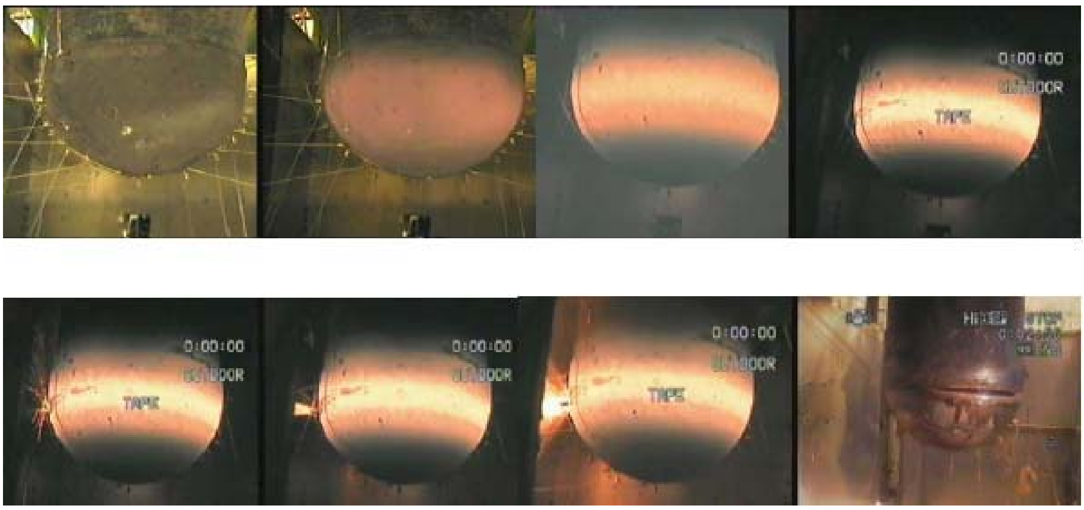


Figure 7. Photographs of the sequence of the EC FOREVER-4 test.

Figure 7 shows the photographic sequences of the typical EC FOREVER test (EC FOREVER04 Test). After ~12 hours of creep, when the vessel's 5% creep was observed, water was poured into the vessel. The procedure was designed to allow a crust to form near the vessel wall, so that during the vessel creep a gap may form between the vessel wall and the crust. In these tests, maximum external wall temperature was ~875°C at 73° from the bottom of the vessel.

Figure 8. The in-vessel configurations of the FOREVER-EC4 test (left; failed vessel) and EC5 test (right; non-failed vessel).

However, no gap cooling was observed in the experiment. Except in the top part, the cooling rate was very slow. The extent of the quenched layer is 6~8 cm only from the top surface of the melt pool (Figure 8). The maximum upward heat flux was 1.8 MW/m^2, which decreased to 0.3 MW/m^2 in about 300 seconds and later degraded further. This behavior is quite similar to that found in the MACE/MCCI experiments for ex-vessel melt coolability.

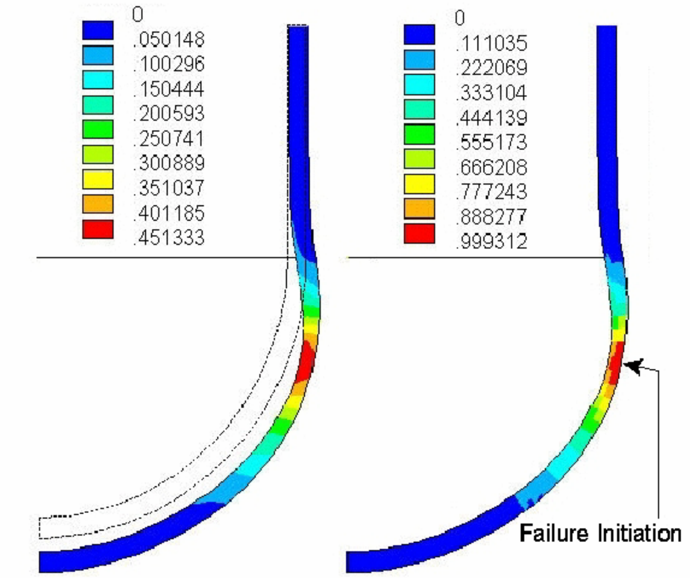


Figure 9. Distribution of the equivalent creep strain (left, max. 0.45) and the damage (right, max. 0.9993) at calculated failure time of t = 4:05h (38 kW, 25 bar, Experiment EC2). ANSYS calculations were performed by H. Willschuetz *et al.*, using the KTH-developed ECCM (effective-conductivity-convectivity model) model for simulation of natural convection heat transfer in volumetrically heated

melt pools.

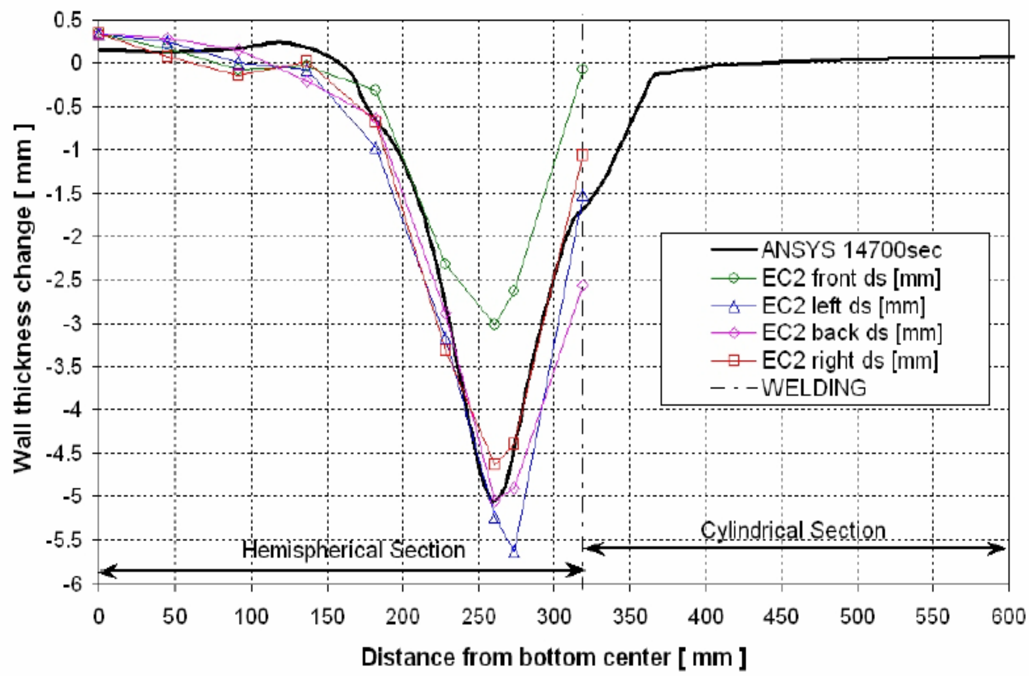


Figure 10. Wall thickness change along the meridian line of the vessel at failure time (FOREVER-EC2 experiment). ANSYS calculation by H. Willschuetz.

2.1.4.2 Research Activities

During the APRI-5 period, the focus was placed on mechanistic and comparative analysis [32, 33, 38] of the FOREVER test results and examining their relevance to various reactor prototypic scenarios. The work [38-42]was carried out in collaboration with scientists from Forschungszentrum Rossendorf (FzR) Institute of Safety Research. A coupled thermal-structure analysis of FOREVER experiments was performed using the ANSYS code (Figure 9 and Figure 10).

2.1.4.3 Results, Lessons Learnt and Recommendations

The results and lessons learnt from the FOREVER test and analysis and further recommendation are as below:

- In FOREVER-EC4 test with American reactor steel, failure time is reduced by almost an hour compared to that for the French reactor steel under similar thermal and pressure loads. Consistently, failures occurred near hot zones at elevated angles (from the vessel bottom) when lower heads were nearly filled with melt. In all the cases, the failure crack traveled circumferentially. Failure length in the American steel covers 97^0 circumferentially. More melt (~70%) is discharged in a vessel made of the American reactor steel than that of the French reactor steel. Slightly higher creep strain (~3%) values are observed at failure in the French reactor steel than those for the American Reactor steel.

- The FOREVER analysis with ANSYS thermo-mechanical model, using a creep data base and ECCM (MVITA) model – both developed in the EU FP4 projects, shows a good agreement with the measured data.

- It was noted in the FOREVER process that the creep deformation caused the vessel wall thinning that further accelerates the creep process. Accurate simulation of the vessel thinning is therefore critical to the quantitative prediction of vessel failure timing.

- The insightful analysis results for FOREVER, as well as similar results from simulation of LHF and OLHF tests with finite-element codes, confirms that the vessel deformation and creep process, and even the failure time, can be predicted reasonably well by a 3D computational structural mechanical code, given an adequate description of history and distribution of thermal loads. Severe accident codes (lumped- parameter models) are not equipped to do the same, due to their lack of capability to accurately present spatial distribution of thermal loads and track the vessel wall thinning.

- For in-vessel coolability tests (FOREVER-EC5 and EC6), history of the upward heat transfer from the melt pool to the water was derived from an analysis with the RELAP-5 Code. The post–test examination confirms that:
  - no “gap cooling” was found active during the FOREVER in-vessel melt pool coolability process, even when the water was poured into the vessel after 5% creep was observed in the vessel,
  - water ingression in the melt pool was limited to an upper debris layer of 6 to 8 cm, and
  - maximum upward heat flux was estimated of ~1.8 MW/m^2, which decreased to 0.3 MW/m^2 in about 5 minutes and later degraded further. This behavior is quite similar to that found in the experiments of the MACE Project for ex-vessel melt coolability

- To fully understand the implication of the FOREVER-EC5 and EC6 test results, a more comprehensive and mechanistic analysis is recommended, e.g. to study the effect of scale (1/10), materials (stickiness to the vessel surface), and heating method on in-vessel coolability in FOREVER and reactor scenarios.

- Remarkably, none of FOREVER experiments was performed to study late-phase melt progression and vessel failure mechanisms in the BWR lower head configurations. Competition between the creep-induced, global failure mode and the local, penetration failure mode is central to the prediction of melt discharge characteristics during a severe accident in a BWR plant. A detail mechanistic analysis for BWR is recommended, which can serve as a basis to suggest experiments on BWR vessel failures, and whether the existing FOREVER infrastructure and technology can be used for creating relevant observations and scalable data base.

- In the SARNET project of the 6th framework of EU programs, KTH-FOREVER experimental database is under consideration to use for a joint benchmarking test to investigate the integrity of vessel and failure mechanisms.

2.2 Steam Explosions

2.2.1 MISTEE Programs: A Study of Micro-Interactions in Steam Explosions

2.2.1.1 MISTEE Experiments

The ultimate objective of the steam explosion study at KTH is to develop a basic understanding of micro-interactions in steam explosion, with a hope to identify mechanisms which may limit the explosivity of molten corium in a prototypic severe accident scenario with fuel-coolant interactions (FCI). The working hypothesis is that physical properties of corium UO_2-ZrO_2 as a binary oxidic material may have been responsible for the low explosivity of corium as observed in FARO, KROTOS and some other real-corium experiments. The evidence is however far from being conclusive, so that extrapolation of the observed behavior to reactor scenarios is not possible without an in-depth understanding.

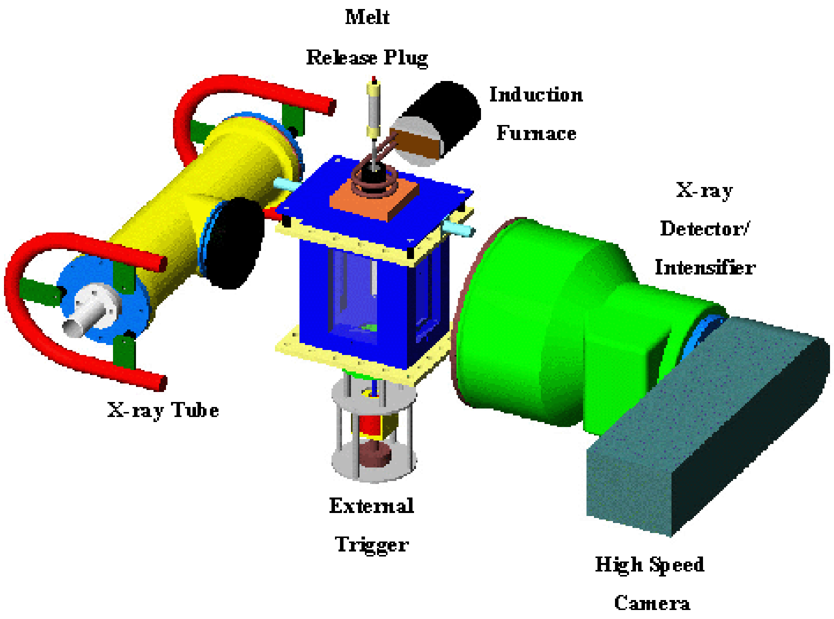


Figure 11. The MISTEE Facility

With this motivation, an experimental program named MISTEE (**M**icro-**I**nteractions in **S**team **E**xplosion **E**xperiments) [43-55] was initiated at KTH-NPS and supported by APRI over the past several years. The MISTEE program focuses on a single-drop steam explosion. The key idea is to enable visualization and quantitative characterization of melt drop fragmentation processes, so to develop a basic understanding of how various parameters and properties govern steam explosion energetics.

The MISTEE facility is shown in Figure 11. The MISTEE system consists of: an interaction chamber, an induction melt furnace, an external trigger system, an operational control system, and data acquisition and visualization systems. The test section is a rectangular tank (180x130x250mm) with 4 view windows (70x150x 24mm) with a 1kW immersion heater. A piezoelectric pressure transducer is flush-mounted on the center of a test section wall. K-type thermocouples are used to measure temperatures of the molten droplet at the furnace and water temperature inside the test section. Two K-type thermocouples are used to measure temperatures of the molten droplet at the furnace and water temperature inside the test section.

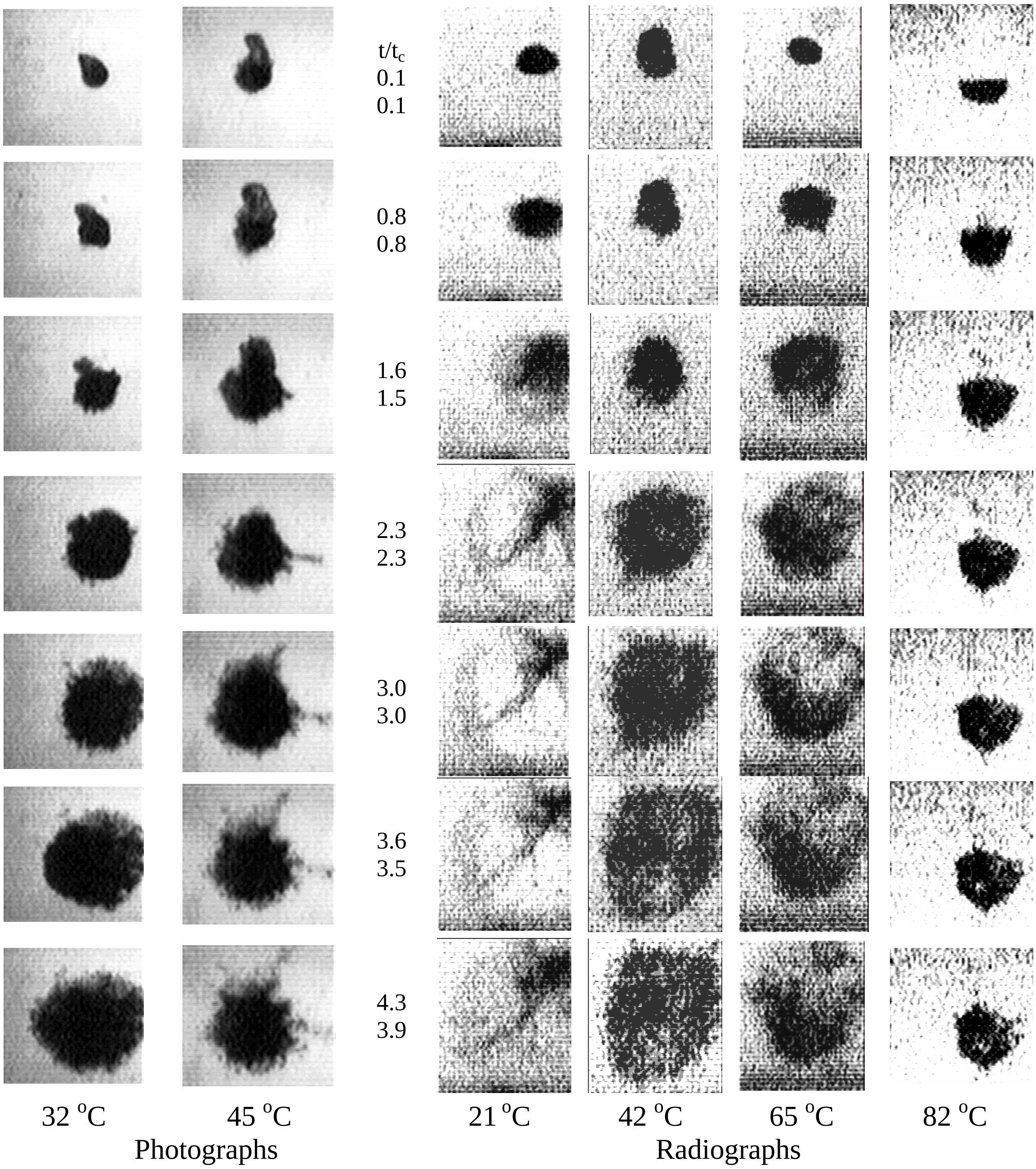


Figure 12: Selected photographs (left) and X-ray radiographs (right) of the vapor explosion of 0.7g tin drops at 1000 °C in different water temperatures.

Furnace with the voltage and current up to a 260V and 40A, respectively, consists of a graphite cylinder (40mm O.D. x 50mm) and an alumina crucible (20mm I.D. x 30mm) with a 4.1mm hole at the center of the bottom. A Boron-nitride plug as a melt release plug is used to block the crucible bottom hole during the melting and is lifted by a pneumatic piston to release the melt drop. The external trigger, located at the bottom of the water tank, is a piston that generates a sharp pressure pulse similar to a shock wave. The trigger hammer is driven by a rapid discharge of a capacitor bank consisted of three capacitors ($400V_{dc}$ and 4700 mF each) that impacts on the piston to generate a pressure pulse.

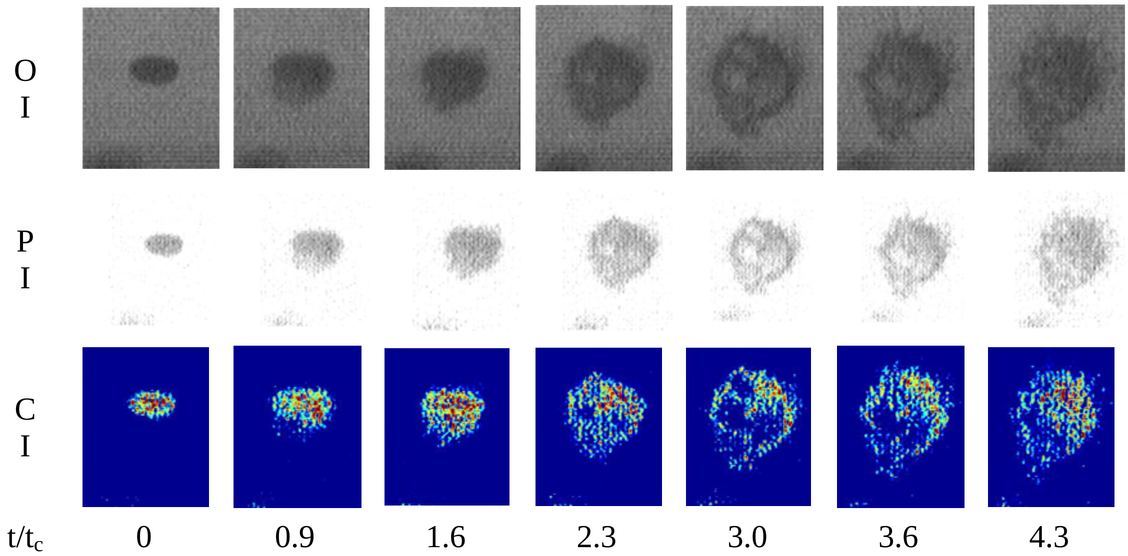


Figure 13: X-ray radiographs (right) of the vapor explosion of 0.7g tin drops at 1000 °C in 22 °C Water. Image size for the original radiographs is 29.3x24.6mm (199x167 pixels). OI: Original Image, PI: Processed Image, CI: Calibrated Image

The visualization system, photography and radiography, consists of a continuous X-ray source tube (Philips continuous X-ray, MCN 323) with the maximum voltage of 320 keV and the maximum current of 22mA, an X-ray converter and image intensifier (Thomson TH9436 HX) with a view window of 290mm and a high-speed video camera (Redlake HR2000 Motion Scope) with the maximum recording time of 4 seconds at the maximum frame rate of 8000. The X-ray converter and image intensifier powered by a high voltage power supply (Thomson TH 7195) has three different magnification modes. In the tests presented in this paper, no magnification mode was selected. X-rays are detected on the input phosphor screen with a CsI crystal layer and converted into photoelectrons that are accelerated, amplified and converted at the output phosphor screen to visual light. The resolution of the X-ray image is 56 line pairs per centimeter. The image size of the high-speed camera at 8000 fps is 80x70 pixels.

The MISTEE facility is located inside a 0.6 m thick reinforced concrete containment (3.8m x 3.8m x 3.9m), for the X-ray radiation shielding during the tests, The operation of the test is controlled remotely outside the containment.

2.2.2 Research Activities

The previous research activities of the MISTEE program focused on to identify the mechanical processes of fine fragmentation of molten liquid drop in subcooled water during the vapor explosions as well as to quantify the dynamic behavior of vapor bubble and associated fragments. In addition, the quantification of melt fraction distribution during the fragmentation process was performed by a series of image processing and calibration tests.

For the visualization of X-ray radiography as shown in Figure 12 [47], High-speed continuous X-ray images revealed the complexity of the melt fragmentation process of the vapor explosion even in a single drop sub-gram scale. A series of calibration and image processing techniques enable to construct a two-dimensional melt fraction map during the vapor explosion processes as shown in Figure 13 [47].

One significant improvement of our X-ray radiography system in the MISTEE facility has been achieved by adding additional high-speed CMOS camera (Redlake HG50LE Color CMOS Camera, 100,000 fps maximum). This improvement provides the simultaneous synchronized visualization using two high-speed cameras, one for X-ray radiography and another for photography, called SHARP (**S**imultaneous **H**igh-Speed Visual **A**cquisition with X-ray **R**adiography and **P**hotography) (see Figure 39) where synchronized visual data for vapor bubble and melt fragment dynamics, will enable the accurate quantification of the steam explosions.

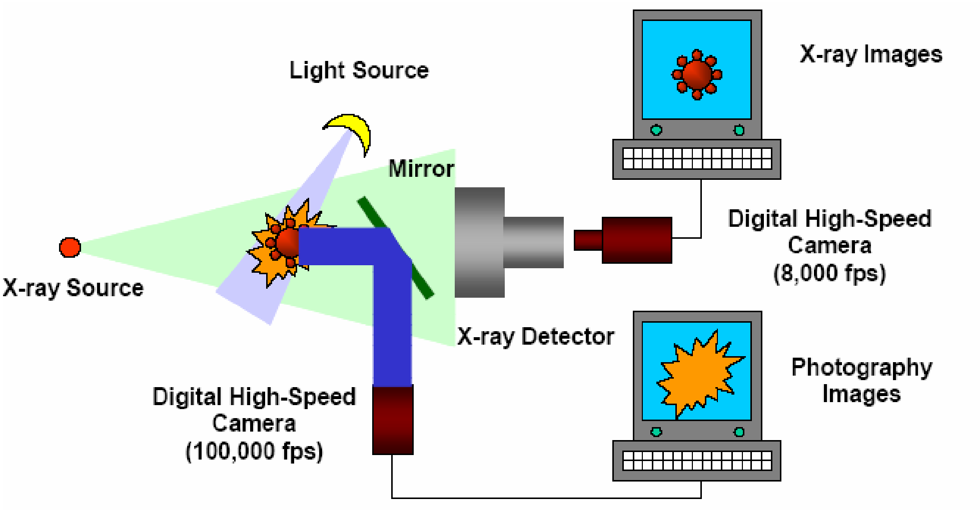


Figure 14: The schematic of the SHARP system.

One high-speed camera (photography) visualizes the dynamic behavior of vapor film surrounding a melt drop during the vapor explosion process. This information will provide data on the interaction zone of steam-melt-water mixture as well as the transient steam bubble dynamics. The data on interaction zone will be used to quantify the volume fractions of each component involved in vapor explosion derived from the image data from the X-ray radiography. The data on the transient bubble dynamics in combination with dynamic pressure signals will be used to estimate the energetics or explosivity, of the vapor explosion, in terms of explosion conversion ratio (the ratio of work done by the explosion process on the environment to the total initial energy content of the melt droplet).

The other camera (X-ray radiography) visualizes the melt fragmentation process during the explosion phase of vapor explosion. This image data will provide the visual information on the fine fragmentation and triggering processes and eventually be quantified after a series of calibration tests. This transient fragmentation data will be used to evaluate the current-existing analytical fragmentation models and to propose a new model if necessary. In addition, the X-ray image data will provide the characteristic and location of initial triggering and small-scale propagation processes. Dynamic behavior of finely fragmented melt particles will be also important data to evaluate the existing analytical explosion models which employ local heat transfer among the fine particles, un-fragmented melt, vapor and water in the interaction zone.

In analysis, a bubble dynamic model was developed to explain the cause of bubble generation, bubble dynamics and melt fragmentation. The stability analysis of vapor bubble during growth and collapse was investigated and correlated to predict the size distribution of melt fragments.

2.2.3 Results, Lessons Learnt and Recommendations

The followings are the previous results lessons learnt and further recommendation of the activities in the MISTEE facility:

- The relatively small portion of a single drop melt was always pre-fragmented by the first perturbation mostly induced by the external shock wave. The major energetic FCI occurs when pre-fragmented drops were triggered.

- The oscillation of vapor bubble during expansion and collapse continuously induces the energetic FCIs and generate finely fragmented melt debris.

- For highly subcooled water, the small-scale stratified explosion initiated at the circumference or lower hemispherical region of an ellipsoidal or spherical droplet, respectively and propagated along the melt surface.

- For lower subcooled water, the vapor/gas pocket formed during the impingement of molten tin drop into water and film boiling heat transfer in water provide an extra triggering source. The maximum expansion diameter of fragmented particles and vapor bubble reached 3~3.5 times the initial diameters.

- X-ray radiographic images showed a shell of fragmented melt particle near the vapor bubble boundary during the explosions. Transient spatial distribution map of melt fragment during the explosion was obtained. However, further improvement in X-ray image is needed for accurate quantitative measurement.

- Simultaneously synchronized high-speed visualization with X-ray radiography and photography system is a promising tool to investigate the vapor explosion processes.

- The metallic melt tests with molten tin droplet have been completed. The evaluation methodology of energetics of single drop FCIs was developed and preliminary analysis showed less than 0.5% conversion ratios were estimated. The evaluation used the experimental data such as transient pressure signal and vapor bubble dynamics visualized by the high speed photography. X-ray radiographic images reveal the transient structure of FCIs at various thermal conditions.

- High temperature oxidic melt tests are highly recommended.

Chapter 3
New Research Framework Toward to Resolve Risk Significant Severe Accident Issues in Nordic Nuclear Reactors

3.1 Background

Over the past 13 years KTH Division of Nuclear Power Safety (KTH-NPS) has had an extensive and substantial research and education program on severe nuclear accidents in LWRs, their phenomenological modeling, prediction and consequence assessment. During this period, KTH research has significantly leveraged on several large-scale research projects on severe accidents funded in the EU Framework Programs 4, 5, 6, Swedish APRI program as well as NKS-R program at KTH-NPS. This has made it possible to develop at KTH-NPS unique world-class infrastructure for experimental research as well as to advance the state of the art in several areas of severe accident phenomenology.

In fact, names of KTH, FOREVER, MVITA, POMECO, SIMECO, COMECO and MISTEE have become frequent buzz words in severe accident community, reflecting KTH contributions and its position in international arena.

The main objective of KTH research is to improve understanding and thereby reduce uncertainty in quantification of

(a) vessel behaviors during a late phase of in-vessel core melt progression,
(b) ex-vessel fuel-coolant interactions (steam explosion), and
(c) ex-vessel debris coolability.

In the NKS-ExCoolSe project, the last two items have been focused since they present a threat to containment integrity in BWR plants, which employ deep cavity flooding for severe accident management (SAM).

KTH research was also structured to provide data which can be used to evaluate effectiveness of several measures, which have been identified and proposed to mitigate consequences of ex-vessel steam explosion and debris non-coolability in BWR plants [8-11]. The mitigative measures studied pertain to possible avenues

(a) to keep the core debris inside the reactor pressure vessel (RPV), e.g.
    i. coolant supply atop the debris and subsequent "gap cooling",
    ii. coolant supply through Control Rod Guide Tube (CRGT).
(b) to enhance ex-vessel debris coolability by "downcomers"
(c) to suppress steam explosion energetics e.g. using additive agents in containment water.

3.2 Learnt from Past and Outlook

Based on the field's current state and on the progress made in the previous years in both experiments and analyses, it is suggested to focus KTH severe accident research in coming years on few key, selected items which largely relevant to the NKS-R program. The programmatic objective is to enable the ***resolution of two long-standing severe accident issues*** in the Swedish BWR plants, namely ex-vessel steam explosion and ex-vessel debris coolability.

- Practically, such a resolution requires plant-specific considerations and comprehensive treatment of scenarios and phenomenological uncertainty. While such a treatment is not part of the phenomenological research, we will use a probabilistic/deterministic framework to effectively guide research on phenomena, through scaling, experimental design and procedure, data acquisition (knowing what to extract), interpretation (focusing on relevance to reactor conditions), and generalization. The two-way connection between KTH research and plant safety analysts (Level 2 PRA) has been established. Substantial, sometimes intense, dialogues during the year 2005 among parties involved have helped to reach a consensus in planning the next step. More importantly, the avenues are clear for what and how KTH research outcomes can benefit the plant safety assessment.

Resolution of the two severe accident issues in Asea-Atom BWR plant is a formidable task, given existing uncertainties and limited resources internationally and nationally available for severe accident research, e.g., as compared to late 1980s and 1990s. In this context, the above-mentioned bridge between phenomenological research and plant safety analyses is furthermore paramount.

I. In in-vessel melt-vessel interaction area, our approach is dual.

> **I.a.** On the one hand, we are cognizant that cooling and possible retention of core debris within the RPV are most cost-effective and safety-effective. It is therefore useful, in PRA sense, to establish conditions (coolability map) by which in-vessel coolability and retention can be achieved, either by coolant injection into RPV from an independent system or by using the existing CRGT coolant supply. This is planned to be achieved through interpretation of existing experiments and additional mechanistic analyses, including processes of melt relocation to the lower head, and debris bed formation in the vessel lower head. These factors influence the time for debris bed to dryout, reheat and remelt, and hence they affect the effectiveness of coolant supply to retain debris in-vessel.
>
> **I.b.** On the other hand, we are driven to establish the (low) likelihood of large melt pools formed prior to vessel failure. Risk-wise, scenarios with massive melt release are most prone to large-scale steam explosions and formation of hard-to-cool cakes on the drywell floor. Our line of pursuit here is that instrumentation guide tubes (IGT) are likely to fail well before a large molten pool is formed in the BWR vessel lower head. Consequently, corium discharge is predominantly gradual (in dripping regime) through a single or multiple failure sites (IGTs). Both experiments and mechanistic analyses are required for this task.

II. In ex-vessel debris bed coolability area, we identify debris bed formation as a key to the resolution. Results of initial DEFOR tests) were encouraging. We will use the DEFOR experiments to motivate the analysis and modeling. Another key to the resolution is the three-dimensionality effect, which facilitates coolant ingression from side and bottom and two-phase natural circulation for the porous bed's cooling. We will use a three-dimensional model, validated on POMECO, DEFOR (cooling stage) and other experiments, to establish a coolability map, which can then be used in a system code or otherwise to support Level 2 PRA.

III. In steam explosion area, substantial uncertainty remains after 30 years of worldwide intensive research. For Nordic BWR plants, risk-significant situations occur when a large mass of superheated metal melt and oxidic melt is discharged to a deep, subcooled water pool. While we will keep our eyes to distill information from international research (SARNER, CSARP), our program in this area focuses on micro-interactions of molten droplet and coolant, aiming to understand and quantify the effect of the melt drop's outer crust formation on energy conversion. Our research is driven by a hypothesis that corium properties as a binary (multi-component), non-eutetic mixture largely suppress the explosion energetics. The work will continue with MISTEE experiments, whose analysis will be supported by a parallel effort in computational multi-fluid simulation.

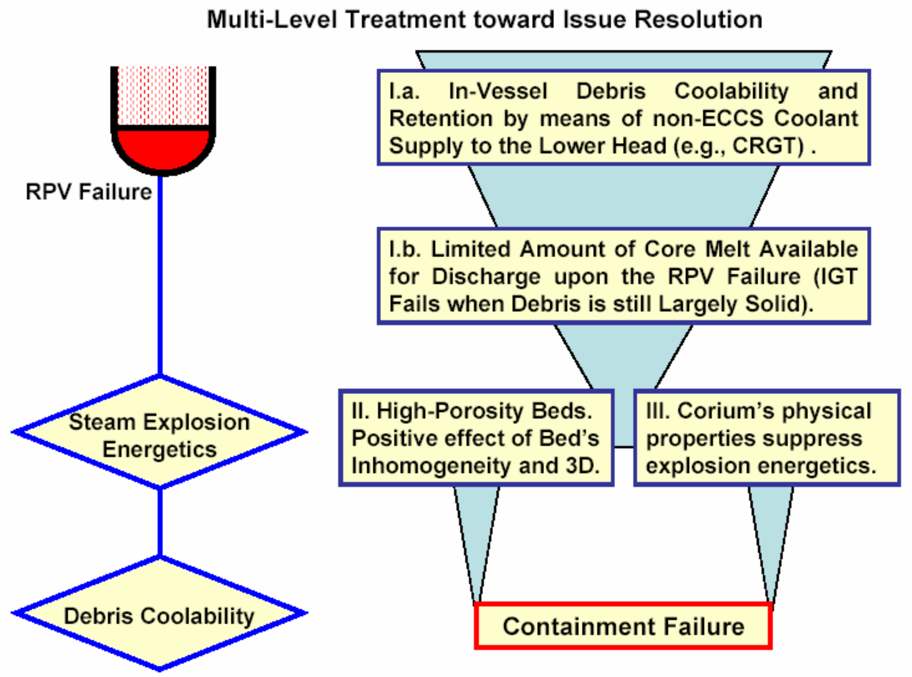


Figure 15. The connection between KTH research and quantification of risk of containment failure. KTH research addresses "limiting" mechanisms. Except for I.a (which calls for a mitigative measure), the others (I.b, II and III) aim to establish and exploit the hidden margins.

In summary, the proposed work aims to show (see I.a) that for a core damage accident, in-vessel cooling and retention are likely, given an independent coolant supply (e.g.

through CRGT). We will then show (in I.b) that the discharge is predominantly gradual and hence posing insignificant threats to containment integrity, if IVR is insufficient to prevent vessel failure. Finally, we will show (in II and III) that a proper account for realistic bed formation and corium properties bring both steam explosion and ex-vessel debris coolability issues to rest. Thus, our research exhibits a consistent, focused approach oriented to issue resolution through multiple levels of defense. Formulation of this approach (Figure 15) has become possible thanking to the substantial insights gained from KTH works during previous years.

3.3 New Approaches

The approach taken in KTH research is triple-pronged.

First, integral experiments were designed and conducted, including experiments using high-temperature binary-oxide melt, at respectable scales and in configurations that maximally reflect the plant and reactor geometry (given technological and financial constrains). The idea is to use these experiments to motivate phenomenological research, to identify new aspects which cannot be otherwise discovered through pure analyses, and to gain insights into complex physics that governs the process. The data are also useful for model development and validation.

Second, we pursue physics-oriented experiments and related mechanistic analyses, which took off from the substantial funding in previous EU projects and recent support of Swedish APRI program for a PhD project (MISTEE) and a project on two-phase natural circulation in internally-heated porous beds (NCDC). The idea of these works, both basic experiments and analyses, is to complement integral experiments with in-depth understanding of underlying mechanisms, to identify and quantify the effect of melt materials and coolant chemistry on steam explosion energetics, bed's inhomogeneity on coolability; in short, separate effects which are not possible to study in integral settings.

Third, increasingly KTH research is structured to bridge between experiments, data, basic understanding, to models, codes and finally plant safety assessment. During the year 2005, a substantial effort was directed toward examining previous data and knowledge, obtained both in KTH works and international programs, from the BWR application perspective. This also includes analysis of models and capabilities in severe accident codes used in industry, research and regulatory organizations.

In this report, summary is given for all programs carried out at KTH-NPS, both with respect to "Activity during 2003-2005 period" and "Results, Lessons Learnt, and Recommendations". In several areas, substantially new data were obtained, which facilitate the analysis and model development. In some other areas, the works led to new insights, reduction of uncertainty and suggestions for further researches.

In fact, research on severe accidents at KTH-NPS serves as platform for advanced education and training. This educational component of our program fits excellently with the academic mission of KTH as Sweden's premier school for engineering science. During this period, 20 researchers obtained their advanced training in severe accident experimentation, severe accident modeling, and plant safety assessment through their active participation in research projects at KTH-NPS. After graduation our students and trainees went to work at major Labs in Europe and beyond. In addition, Professors B.R. Sehgal and T.N. Dinh are contributing, with other European lead researchers under SARNET umbrella, to writing a book on “LWR Severe Accident Safety” (edited by Prof. Sehgal). This book summarizes advances made in EU research in severe accident safety, including major achievements at KTH. The related materials have been used in teaching EU-funded courses on “Severe Accidents” and “Probabilistic Risk Analyses” for students and researchers.

This final report summarize the recent results obtained from the KTH severe accident research program relevant to the objective of the ExCoolSe project sponsored by the NKS-R program. The EXCOOLSE project has been integrated with, and leveraged on, parallel research program at KTH on severe accident phenomena – the MSWI project which is funded by the APRI program, SKI in Sweden and HSK in Switzerland and produced more understanding of the key remaining issues. Recently, the critical assessment of the existing knowledge and current SAMG and designs of Nordic BWRs identified the research focus and initiated the new series of research activities toward the resolution of the key remaining issues specifically pertaining to the Nordic BWRs.

Chapter 4
Coolability of Particulate Debris Bed

4.1 DEFOR Program: A Study of Debris Bed Formation

4.1.1 DEFOR Experiments

The DEFOR (**DE**bris bed **FOR**mation) program [56, 57, 58] was initiated in 2005, to study debris bed formation, and support the quantification of characteristics of a debris bed formed upon fuel-coolant interactions (FCI).

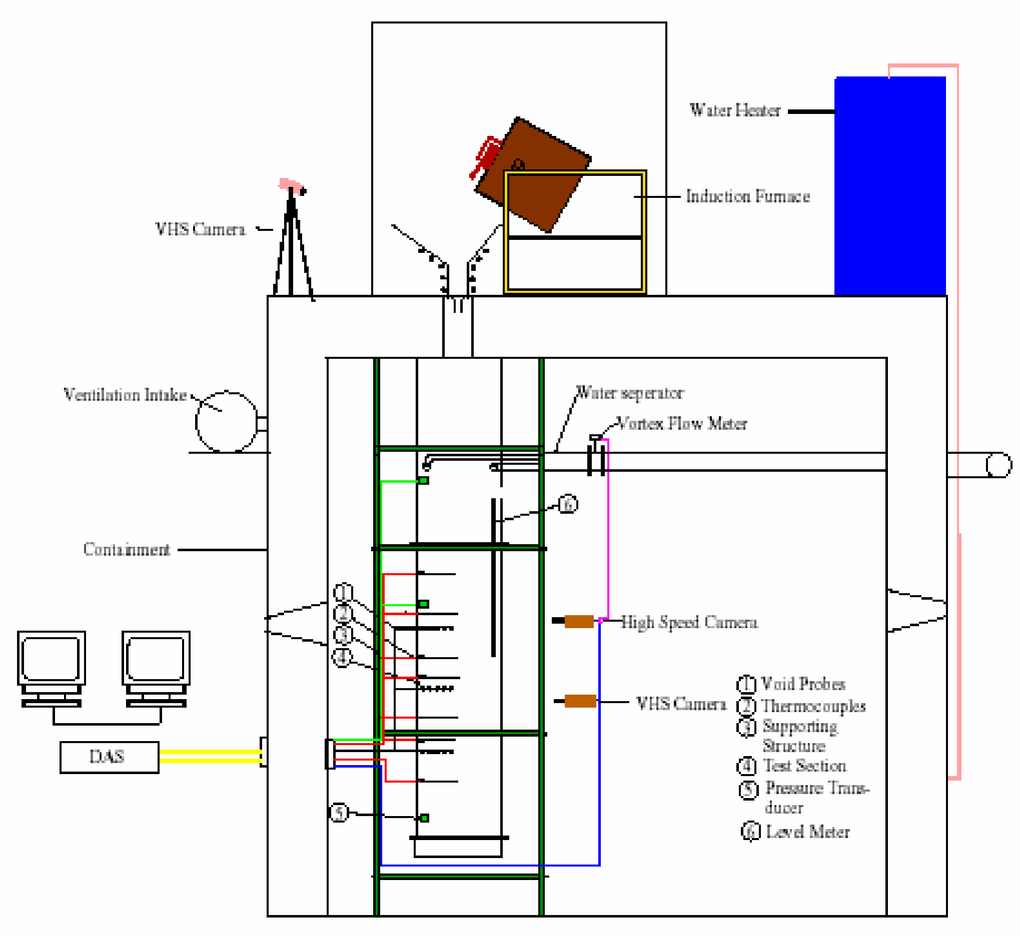


Figure 16. The schematic of the DEFOR facility (previously MIRA-20L).

It is noted that extensive programs in FCI areas were all focused on characterization of the FCI premixing or explosion stages. Characteristics of the resulting debris bed settled on the pool bottom were not emphasized. There exist few experiments (e.g., CCM, FARO) that provided a data base for particle size distribution and bed's averaged porosity. However, conditions in such experiments were far from those relevant to situations in BWR plants, namely, a core melt is discharged into a deep, highly-subcooled water pool in the lower drywell cavity. The goal of the DEFOR program is to fill this gap in knowledge, and most importantly, to motivate analysis and modeling activity in this area.

4.1.2 Research Activities

The DEFOR test facility [56] is assembled practically from the MIRA-20L facility, which was used at KTH-NPS to study high-temperature binary-oxidic melt jet breakup (Figure 16).

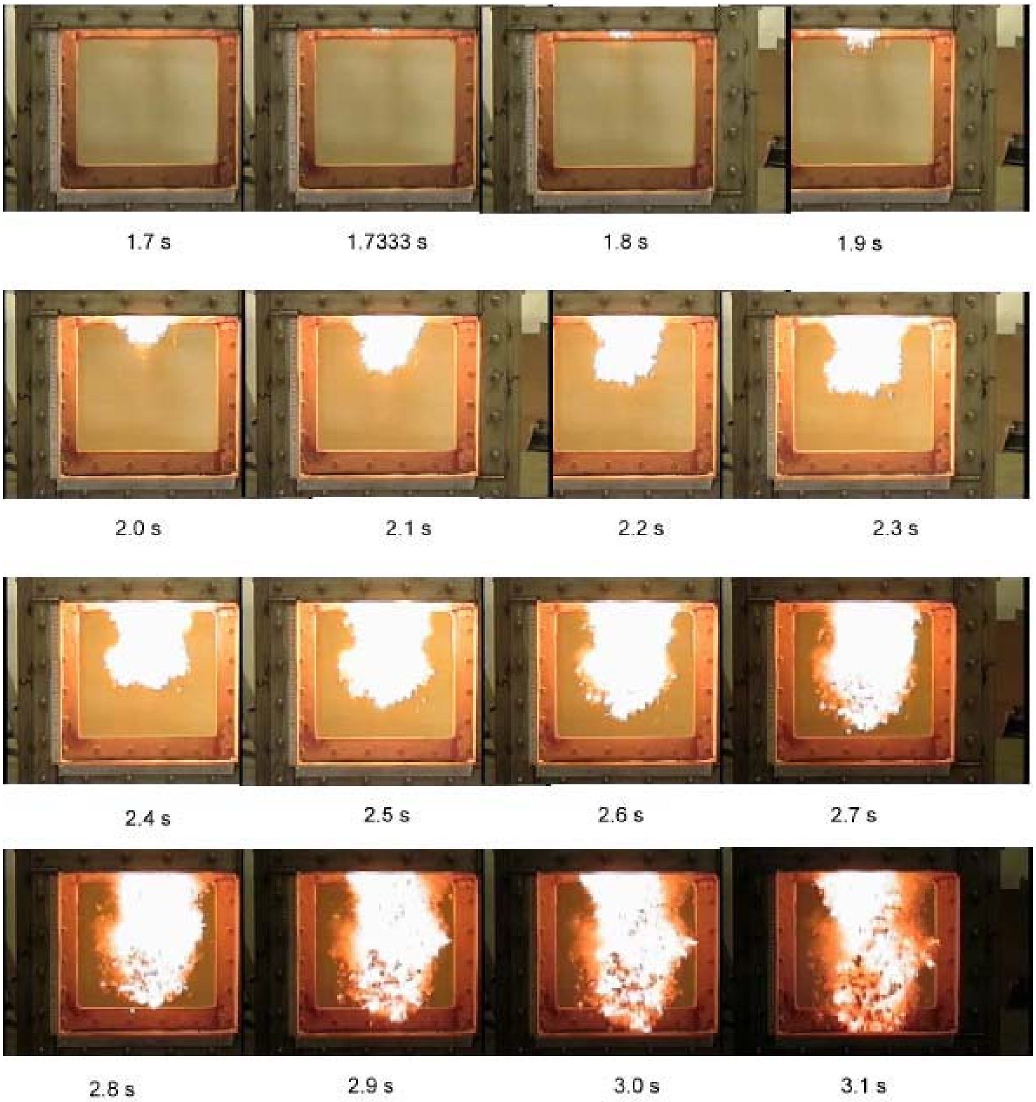


Figure 17. DEFOR-1 test: Fragmentation of a high-temperature binary-oxidic melt jet in a subcooled water pool, with subsequent intense debris-coolant mixing and heat transfer, and formation of a high-porosity debris bed on the tank bottom.

An induction furnace is employed in DEFOR test to generate up to 20 liters of oxidic melts. In DEFOR-1, 2 and 3 tests (Figure 17) conducted in November-December 2005 period, up to 7 liters of CaO-B_2O_3 melt (max. 1250 ^oC) was used. The DEFOR-4, 5, 6 and 7 tests were also conducted in January-February 2006. In particular DEFOR-7 test was conducted with higher density binary oxidic melt than one used in the previous 6 tests to investigate the material property effect and density effects on the debris bed formation. The jet diameter (nozzle) is 2 cm, and the water depth in the tank is 65 cm. An array of thermocouples (Figure 18) is installed in the tank's lower region to measure temperature in the debris bed as it forms on the tank bottom. Water temperature was varied from high subcooling (88K) to low subcooling (3K), to represent typical ex-vessel and in-vessel situations, respectively.

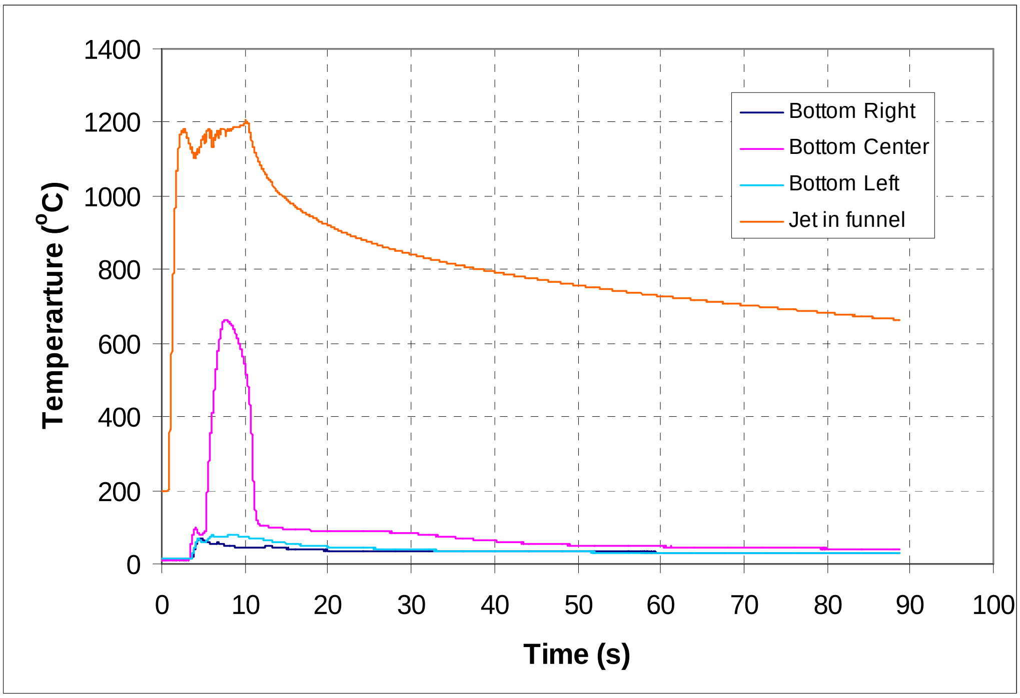


Figure 18. Temperature as measured by thermocouples in the funnel nozzle, and in the tank bottom.

4.1.3 DEFOR Analysis

4.1.3.1 One-Dimensional Analysis of Thermal-Hydraulics in Porous Bed

One-dimensional model [58] to analyze the thermal-hydraulic behavior of the ex-vessel debris bed in the deep water pool formed during the corium melt ejection out of the vessel to the water-filled cavity. The model calculates two-phase flow in a debris bed with water fed from the bottom of the bed. The model considers the natural circulation driven by single-phase downward flow in side channel and two-phase upward flow in debris bed and the multi-ring and layer configuration of the bed. The model only considers steady-state and thermally equilibrium conditions.

Pressure gradient along the debris bed is calculated by the two-phase Lachart-Martinelli friction pressure drop model [4] with Ergun porous media parameters [5] for the debris bed. Simple energy balances for subcooled single phase flow in the side channel and for the saturated two-phase flow in the bed with the internal heat generation is considered.

This one-dimensional model has advantages of (a) control and demonstration of the main phenomena and physics of two-phase flow in porous media, (b) easy validation against experiments (c) easy performance of parametric study for development of coolability map and (d) easy update of correlations based on experimental progress. However, the analysis is limited (a) only for one-dimensional, steady-state and thermal equilibrium two-phase in porous flow (only for homogeneous bed and macroscopic heterogeneous bed and (c) only applicable to the coolability analysis of a debris bed with coolant bottom-fed.

4.1.3.2 Research Activity

The validation of the current model was carried out by examining the friction law of two-phase flow in porous media, in micro-channel, dryout heat flux, and pressure gradient in debris bed [58].

For the two-phase friction pressure drop, the Lockhart-Martinelli correlations are extensively applied in the design of flooded-bed reactors for two-phase pressure drop through packed beds, with acceptable prediction accuracy. The correlations are also employed and validated against two-phase flow in micro-channels which have certain similarity to pores in porous media.

The dryout heat fluxes (DHF) calculated by the current model for both top-flooding and bottom injection cases are compared with the well-received 0-D Lipinski model [6] and recent experimental data [7]. The analysis showed the reasonable match with both results. The calculated DHF for bottom-fed bed predicted 100 ~ 160% higher than that of top-flooding bed. The data from both DEBRIS facility and Bang et al [7] all show a significantly enhanced DHF in bottom-fed bed. However, forced injection is used in their experiment, which is different from the present study (natural circulation driven injection). Moreover, the predicted pressure gradient is in disagreement with a set of experimental data obtained from DEBRIS facility at IKE. More verification in this data set is needed. It is believed the model prediction error will be within the error range of Lockhart-Martinelli correlations (±40%).

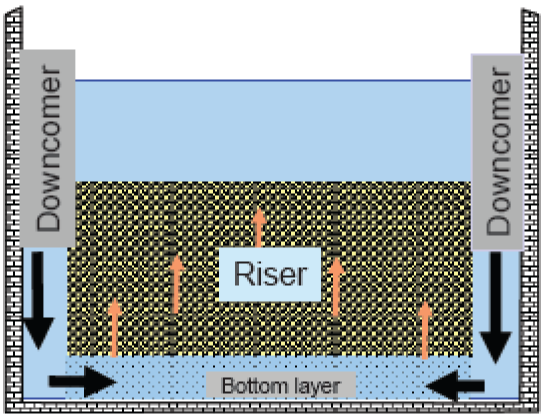


Figure 19. The model schematic for the debris bed accumulated in the Nordic BWR cavity [58]

The first preliminary analysis was performed to evaluate the coolability of ex-vessel debris bed formed in the postulated ex-vessel severe accident in ABB-Atom BWRs.

Figure 19 shows the schematic of the model for the debris bed accumulated in the Nordic BWR cavity. Table 2 listed the calculation conditions for the Nordic BWRs obtained from the MELCOR code analysis.

Table 2. Calculation conditions for Ex-Vessel Debris Bed in ABB-Atom BWR.

Conditions	Values (Reference)
Thermal Power	2500 MW
Cavity Diameter	9 m
Initial Water Depth in Cavity	8 m
Debris Mass	180 tons
Debris Volume (without void)	23.5 m^3
Decay Heat (1~2% thermal power)	25~50 MW
Volumetric Decay Heat	0.6~1.28 MW/m^3
Debris Bed Parameters	
Porosity	0.3~0.6 (0.4)
Debris Diameter	1~5 mm (3mm)
Debris Bed Diameter	4.0 ~ 8.5 m (8.5m
Debris Bed Height	0.69 m

The preliminary results at the reference conditions showed in Table 2 predicted that the exit temperature of the two-phase coolant mixture in the bed becomes exceed its saturation temperature at the decay power of more than 4.5 MW/m^3. It indicated that the debris bed may have sufficient flow to be quenched at the given debris bed characteristic when the coolant is fed from the bottom of the bed. The bed configuration in terms of the bed height and diameter is also examined. The results showed that the DHF increases up to more than 4 times as the bed diameter increases about two times by keeping the same total volume of the bed, i.e., lower the height of debris bed. The effect of the particle diameters and porosity are also examined. The results showed that DHF increases monotonically with the particle diameter and porosity of the debris bed. For the porosity, the DHF already becomes about 3 MW/m^3 at the debris bed porosity of 0.3 and more than 7 MW/m^3 at the porosity of 0.6.

In general, the preliminary results with limited modeling showed the favorable cooling capability of corium debris bed with the coolant bottom injection. However, the model is needed to be validated further with qualified experimental data and to be developed. In particular, transient, two-dimensional model capability will be desired.

4.1.4 Results, Lessons Learnt and Recommendations

Recent DEFOR experiments showed the interesting results on the debris bed formation and characteristics and suggested further refinement of the experiments to obtained the detailed experimental data and insights for the model development.

- DEFOR-1 and DEFOR-2 tests show the formation of high-porosity beds even when the water pool depth to jet diameter ratio (L/D) is a mere 40.

- The bed porosity can be as high as ~75…84% as in the case of DEFOR-2 test, when 7 liters of melt was employed for the test. A significant contribution to the porosity is due to large pieces, which arrived in a later phase of the delivery.

- An increase of debris sizes is thought to have dual origins, which are subject of further study. On the one hand, the water tank temperature has gradually increased over the mixing period. The reduced subcooling may have promoted the increase of debris sizes. On the other hand, the observation (of debris size increase near the end of melt pour) is consistent with our hypothesis that the main concern to debris coolability (largely characterized by bed porosity) is related to the first melt release in the form of coherent jet. Gradual melt release in a later phase is conducive to large particle sizes and roughened shapes that render highly-porous beds.

- The debris particles when settling on the floor can be either quenched or unquenched. However, the DEFOR-1 test analysis suggests that the key requirement appears the solidification of the particle, at least its external layers, to the extent that heat conduction within the particle in a later phase is insufficient to cause the external layer to remelt. Consequently, the particles are separable, and the in-between pores remain unplugged, ensuring the bed's high porosity.

- A scaling rationale and mechanistic analysis are required to guide further experimentation with DEFOR tests. It is recommended to vary the melts, melt composition (eutectic vs. non-eutetic), melt superheat as well as coolant conditions to investigate their effect on bed formation, and provide a broad data base for model validation.

- One-dimensional model was developed for simulating thermal-hydraulics of debris bed with coolant bottom-fed under natural circulation.

    - The model can be employed to study the coolability of both radially and axially stratified bed with non-uniform heating, as well as uniform bed.

    - There are little proper data available to validate the model. However, since the friction law (Lockhart-Martinelli correlations) employed in the present model was validated against data from packed-bed reactors and micro-channels, we believe the model prediction can give insights for debris bed coolability with acceptable error and uncertainty.

    - Through the model, natural circulation driven coolability (NCDC)of ex-vessel debris was demonstrated for an ABB-Atom BWR.

    - In general, coolability is enhanced in the bottom-fed bed, by a factor of around 100% ~160%, in comparison with top-flooding bed.

- Therefore, more refinement of the model to accommodate the modelling capability of inter-ring (radial) flow, bubble plume, two-dimensionality and transient conditions. Both model validation and code development for the closure relations, qualified experimental data are needed.

4.2 MISTEE Program: A Study of Micro-Interactions in Steam Explosions

4.2.1 MISTEE Experiments

The ultimate objective of the steam explosion study at KTH is to develop a basic understanding of micro-interactions in steam explosion, with a hope to identify mechanisms which may limit the explosivity of molten corium in a prototypic severe accident scenario with fuel-coolant interactions (FCI). The working hypothesis is that physical properties of corium UO_2-ZrO_2 as a binary oxidic material may have been responsible for the low explosivity of corium as observed in FARO, KROTOS and some other real-corium experiments. The evidence is however far from being conclusive, so that extrapolation of the observed behavior to reactor scenarios is not possible without an in-depth understanding.

With this motivation, an experimental program named MISTEE (**M**icro-**I**nteractions in **S**team **E**xplosion **E**xperiments) was initiated at KTH-NPS and supported by APRI over the past several years. The MISTEE program focuses on a single-drop steam explosion. The key idea is to enable visualization and quantitative characterization of melt drop fragmentation processes, so to develop a basic understanding of how various parameters and properties govern steam explosion energetics.

The MISTEE facility is shown in Figure 11. Molten drop is prepared in a 6 kW induction furnace and released into a test chamber by lifting the plug. When the melt drop is “in place” (in water pool), an external trigger, located at the bottom of the test chamber, is activated to create a sharp pressure pulse up to 0.2 MPa (measured at the center of test-section wall).

4.2.2 Research Activities

A significant effort was directed toward development and testing of a synchronous imaging system that includes a high speed (max. 100,000 frame-per-second) digital photography and high speed (max. 8000 fps) X-ray (max. 320 keV, 22mA) radiography. The objective is to enable imaging of the drop’s energetic dispersal together with the vapor bubble dynamics. The task resulted in an operational system, called SHARP (**S**imultaneous **H**igh-speed Visual **A**cquisition of X-ray **R**adiography and **P**hotography) as illustrated in **Figure 14**. Advanced image processing techniques were employed to maximize the benefit of the SHARP diagnostic tools.

Single-drop experiments were then performed on MISTEE facility, with SHARP. A majority of the MISTEE tests was performed with a tin drop (0.7g) at the initial temperature higher than 1000 ^{o}C (see Figure 20). Several tests were also conducted with high-temperature binary-oxidic melt drops (see Figure 21). In addition, an additional test section was developed to study explosion with multiple drops (small jets) which aims to reveal any significance of steam explosion's collective behavior on micro-interactions.

To aid understanding of steam explosion, separate-effect studies were performed including analysis of vapor film stability and instability induced fragmentation process in a single drop using 1-dimensional thermal-fluid model, CFD simulation of liquid drop breakup with surrounding vapor layer due to external shockwave, and film boiling phenomena associated with spontaneous steam explosion as well as to evaluate the applicability of new fluids such as nanofluid. On the larger scale, COMETA (**C**ore **ME**lt **T**hermal-hydraulic **A**nalysis) code exercises were performed on the whole sequence of fuel-coolant interaction process, including pre-mixing, explosion triggering, propagation and expansion.

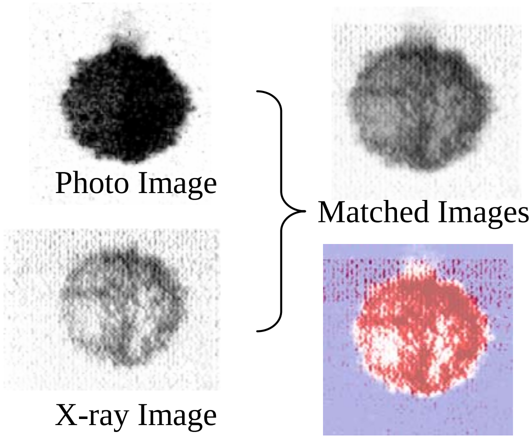
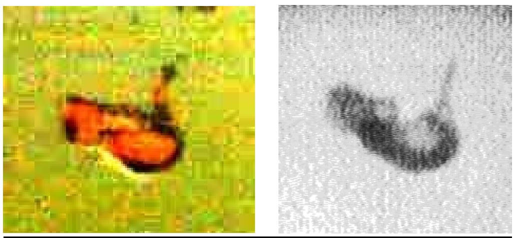


Figure 20. The SHARP images for a highly-superheated molten tin drop steam explosion.



(a) (b)

Figure 21. MnO-TiO$_2$ melt drop (~1400 ^{o}C) in water: (a) photograph image and (b) X-ray image.

Analytical works has also been launched to investigate the various aspects of explosion mechanisms and associated phenomena. The energetics of single drop steam explosions are largely related to the quenching behavior of molten drop. In actual scenario of steam explosion in nuclear reactor, the melt superheat of only about 100~300 K is expected, although the melt temperature is very high (over 3000 K). Such low degree of melt superheat can be a limiting factor for the melt to be energetically exploded. Therefore the detail understanding of thermal behavior during the quenching of very high temperature melt in coolant liquid is of importance. Regarding to this, two separate efforts has been initiated: one is for the solidification behavior of single fuel droplet to look into the mushy zone dynamics and identify the important parameters during the solidification process [43] and another is for the role of radiation heat transfer in cooling and solidification of core melt droplet [45].

For the radiation heat transfer, a radiative-conductive model for cooling and solidification of oxide particles in ambient water is under development. The model takes into account significant role of thermal radiation and possible semi-transparency of millimeter-size particles in the near infrared spectral range.

4.2.3 Results, Lessons Learnt and Recommendations

The MISTEE program [44] to investigate the single drop

- Using the SHARP system (**Figure 14**) imaging of drop explosion processes was achieved at a high speed. For the first time in FCI research, a simultaneous visualization of both melt fragmentation and surrounding vapor bubble dynamics was achieved. Valuable observations were made (as discussed below), which confirm the SHARP benefits.

- It can be seen that a vapor bubble first rapidly grew around the melt drop in a film boiling regime due to triggering and then collapsed to cause an energetic dispersal of the melt debris (first “explosion”), which drove the energy conversion in drop explosion.

- While detailed examination of bubble and melt dynamics is still underway, a preliminary analysis based on the SHARP images has indicated that the melt drop experiences a “pre-mixing” after the triggering. This pre-mixing during the first bubble growth is thought to render a favorable condition (“pre-cracked” melt drop) for liquid jets to penetrate deeply into the melt drop interior when the bubble collapses, hence facilitating the effective fragmentation upon liquid evaporation.

- MISTEE tests conducted with the eutectic CaO-B_2O_3 melt at 1250 ^oC showed no explosion. Melt high viscosity is suggested as being responsible for the resilience. Other binary oxidic materials including higher-temperature, ceramic oxide mixtures MnO-TiO_2 are being tested in MISTEE (Figure 2.5.4.4). Interaction with a partial fragmentation was observed in a triggered experiment with MnO-TiO_2 drop, while subsequent explosion was largely suppressed due to a quick re-establishment of the film boiling on the melt drop and fragments [44].

- Several experiments conducted with additive Al_2O_3 nanoparticles in coolant (nanofluid) showed a slight but noticeable mitigative effect [51]. The result appears consistent with scoping observations in film boiling experiments on water and nanofluid. More analyses are needed to establish the significance of nanofluids on steam explosion energetics as well as physical mechanisms by which nanoparticles influence drop fragmentation.

- In general, SHARP-equipped experiments with variation in coolant properties and melt properties create unique data base needed to discern physical mechanisms that govern the micro-interactions. A systematic study in MISTEE is highly recommended.

- The preliminary results [45] for the radiation heat transfer in corium droplet showed that the character of solidification and solidification time strongly depend on absorption coefficient of particle substance. Semi-transparent droplets are solidified relatively fast. It occurs simultaneously in the particle center (due to thermal radiation) and from the particle surface (due to conduction through the steam layer).

- In contrast to semi-transparent particles, opaque corium droplets are cooled mainly by thermal radiation from the surface. As a result, the solid crust is formed relatively fast on the surface of these particles. The crust layer can prevent from further fragmentation of the corium particle.

Chapter 5
Summary and Conclusions

5.1 Overview

KTH is a leading institution in the EU Severe Accident Network of Excellence (SARNET), being one of the largest contributors to Corium, Containment Workpackaes, the coordinator for “Excellence Spreading” Workpackage, and a key partner in ASTEC-BWR Workpackage. Professor Sehgal is the Chairman of the SARNET governing board. As already mentioned, distillation of knowledge in severe accidents is part of the “LWR Severe Accident Safety” book writing task. KTH (Prof. Dinh) is responsible for sections which address BWR-specific issues.

Through the SARNET-based collaboration, additional capability in analysis was brought to KTH and valuable insights were gained in joint studies. Notable is the successful collaboration between KTH and FzR which was built on an already effective interaction between KTH and FzR (discussed in section 2.5.2). Substantial collaborative program between KTH and IKE-Stuttgart on debris bed formation and coolability has also been started, which leverages the KTH’s DEFOR program on IKE’s modeling and validation works for ATHLET-CD and WABE codes.

ASTEC code for severe accident modeling was originally developed by IRSN and GRS. Within SARNET, further development and validation of ASTEC code are undertaken. Notably, the mainstream development was directed toward PWR. KTH participates in ASTEC tasks to examine and validate the lower head module, using KTH data from FOREVER and SIMECO experiments. KTH also leads the task on specification and modeling needs for ASTEC-BWR. The intention is to enable the development and application of ASTEC for Swedish BWR plants.

The ASTEC-BWR task is leveraged on activity at KTH on severe accident analysis for BWR plants using MELCOR code. In addition, the MSWI/HSK tasks also called for evaluation of uncertainty in models used in MELCOR, MAAP4 for prediction of lower head failure, melt discharge and other ex-vessel melt progression phenomena.

5.2 Results, Lessons Learnt and Recommendations

The experience with these codes reveals deficient features of existing code systems in treating ex-vessel melt progression in the Swedish BWR plants with cavity flooding. Of immediate interest is either lack or inadequacy of models for melt jet fragmentation and fuel-coolant interactions, for steam explosion, for melt spreading, debris bed formation and bed coolability. For instance, the code employs a parametric model which spreads corium over a whole cavity area even when a jet should have been broken up when penetrating into a deep (7-9m) subcooled water pool. The conclusion [8] was reached that the system codes, while useful for certain training/simulator purposes, are not recommended for high-confidence safety analyses of ex-vessel melt progression in Swedish BWR plants, especially when it comes to assessment of threats to containment integrity such as direct containment heating, steam explosion, and debris coolability.

For in-vessel melt progression [11], it is established that all major codes for severe accident modeling have a set of physically-sound models (based on mass and energy balance) for the treatment of melt relocation, debris accumulation and heating up in the lower plenum. However, this apparently-mechanistic capability must be exercised with great care and knowledge of the processes. There is a number of user-specified modeling parameters, and naturally the code results are sensitive to them. Less aware-of is the sensitivity of results to parameters of input deck and nodalization scheme. Often, the system code performance is evaluated and "validated" on early phase of accident progression. Its nodalization is then declared acceptable. However, the code prediction would be misleading until the features important for the late phase are accounted for. Examples related to in-vessel melt coolability and retention are the coolant supply due to CRGT, and heat transfer within the CRGT; external support of CRGT by so-called shootout steel in Asea-Atom BWRs; and details of IGT, which are all not simulated in the existing codes.

Also for in-vessel melt progression, the existing codes lack mechanistic modeling of jet breakup, debris formation, multi-component corium stratification, to name but a few. This deficiency leads to erroneous prediction of heat transfer area between debris bed and coolant in the lower plenum. The code developers have expected the situation and made attempt to address it by providing flexibility in user-specified (arbitrary) heat transfer coefficient which would compensate for the incorrect heat transfer area. Not only is such specification baseless, but just a single (number) parameter is inadequate for various configurations and contact regimes that occur during the whole interaction process.

The analysis of the system code capability points to a need for mechanistic modeling of in-vessel melt relocation processes, including jet breakup, debris bed formation, cooling of the debris bed, heat transfer to the lower plenum structures (e.g. CRGTs), bed's dryout, heatup, remelting of multi-component debris, IGT failures, and corium melt discharge.

KTH investigates phenomenology and uncertainty in quantification of the phenomena of melt-structure-water interactions during a hypothetical severe accident in a LWR. In year 2005, phenomena studied include natural convection heat transfer in a stratified corium pool in the reactor pressure vessel lower plenum (SIMECO program), vessel failure modes and timing (FOREVER program), discharge of melt jet into a water pool and consequent formation of a debris bed (DEFOR program), mechanisms of melt and debris bed coolability (COMECO and POMECO programs), and micro-interactions in steam explosion (MISTEE program). Both analyses and experiments were performed.

Notably, the DEFOR experiments employed high-temperature binary oxidic melts (up to 7 liters) poured into a pool of water with different subcoolings, which correspond to an in-vessel and ex-vessel situation. The MISTEE drop explosion experiments were conducted with highly-superheated metal (tin) and two binary-oxide melts. The SHARP (Simultaneous High-speed Visual Acquisition with X-ray Radiography and Photography) system was successfully developed, tested and used to produce first-of-its-kind visualization of exploding melt drops, with a high temporal and spatial resolution of both melt fragmentation and vapor dynamics. Systematic analysis of steam explosion data base was conducted, with emphasis on the effect of melt material properties.

The KTH activity will continue focusing on the resolving long standing issues, ex-vessel coolability and steam explosion energetics, in Nordic BWRs addressed in the NKS-R ExCoolSe project by implementing the main findings, insights and recommendations derived from the KTH activity in 2005 are as follows

(i) Vessel failure modes and timing can be predicted by 3D structural mechanics code given appropriate thermal load history and distribution.
(ii) While injection of water into the lower plenum was found in FOREVER and COMECO tests to promote debris cooling, "gap cooling" is unlikely an active mechanism and cannot be relied as a safety measure. Further research on gap cooling is not recommended.
(iii) The COMECO tests shows that CRGT cooling has a good potential to increase the likelihood of in-vessel melt coolability and retention in BWR. Further study is recommended.
(iv) Debris bed characteristics present a major uncertainty in the analysis of debris coolability. Debris bed formation must be studied under realistic conditions. Results of the DEFOR experiments suggest the likely formation of high-porosity beds in prototypic reactor scenarios with deep water pools.
(v) Debris bed's three-dimensionality and inhomogeneity are identified as avenues which ease the ingression of coolant into the bed from side and bottom, hence ensuring coolability of even high debris beds. Further studies are recommended.
(vi) Analysis of steam explosion experiments and evidences suggests physical mechanisms by which corium's density, binary solidification, and radiation property may dictate corium's low explosivity. Combined experimental (MISTEE) and computational efforts are highly recommended to establish the effect of corium material properties and their efficacy in prototypic reactor steam explosions.
(vii) Severe accident codes do not provide adequate modeling and prediction of melt-vessel interactions (including vessel failures and melt discharge) and ex-vessel melt phenomena (fuel-coolant interactions and debris coolability). These codes are therefore not recommended for use in applications, when quantification of vessel or containment integrity is concerned.

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<u>DEFOR</u>

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Abstract

The report summarizes activities conducted at the Division of Nuclear Power Safety, Royal Institute of Technology-Sweden (KTH-NPS) within the ExCoolSe project during the year 2005, which is a transition year for the KTH-NPS program. The ExCoolSe project supported by NKS contributes to the severe accident research at KTH-NPS concurrently supported by APRI, HSK and EU SARNET. The main objective in ExCoolSe project is to scrutinize research on risk-significant safety issues related to severe accident management (SAM) strategy adopted for Nordic BWR plants, namely the Ex-vessel Coolability and Energetic Steam explosion. The work aims to pave way toward building a tangible research framework to tackle these long-standing safety issues. Chapter 1 describes the project objectives and work description. Chapter 2 provides a critical assessment of research results obtained from several past programs at KTH. This includes review of key data, insights and implications from POMECO (Porous Media Coolability) program, COMECO (Corium Melt Coolability) program, SIMECO (Study of In-Vessel Melt Coolability) program, and MISTEE (Micro-Interactions in Steam Explosion Experiments) program. Chapter 3 discusses the rationale of the new research program focusing on the SAM issue resolution. The program emphasizes identification and qualification of physics-based limiting mechanisms for both in-vessel phenomena (melt progression and debris coolability in the lower head, vessel failure), and ex-vessel phenomena. Chapter 4 introduces research results from the newly established DEFOR (Debris Formation) program and the ongoing MISTEE program. The focus of DEFOR is fulfill an apparent gap in the contemporary knowledge of severe accidents, namely mechanisms which govern the debris bed formation and bed charatersitics. The later control the debris bed coolability. In the MISTEE program, methods for image synchronization and data processing were developed and tested, which enable processing of MISTEE data obtained with a high-speed Xray radiography and high-speed digital photography. Discussion of uncertainties and severe accident simulation code capability for prediction of the threats on containment integrity is given in Chapter 5.

Key words: LWR, Severe Accidents, Accident Management, Ex-Vessel Melt, Debris Coolability, Steam Explosion, Experiments