SIMECO Experiments on In-Vessel Melt Pool Formation and Heat Transfer with and without a Metallic Layer

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Abstract

This paper describes an experimental program performed at the Division of Nuclear Power Safety, Royal Institute of Technology (RIT/NPS) on a facility named as SIMECO (Simulation of In-vessel MElt COolability). The objectives of the experiments in the SIMECO facility are to investigate (i) the effect of boundary crusts and mushy layers on natural convection heat transfer; (ii) the effects of melt stratification on natural circulation; (iii) the amelioration of melt stratification by turbulent flow fields, and finally (iv) the multidimensional heat transfer in, and between, the melt pool, the top metallic layer and the vessel. Step by step integral experiments are planned.

The SIMECO is a slice-type facility with a semicircular section and a vertical section. Diameter, height and width of the test section are, respectively, 530x620x90mm. Binary salt mixtures are employed as oxide melt simulant, with appropriate molten metals as metal-layer simulants.

Results of SIMECO tests performed are presented, and compared to existing correlations. Results of analyses performed with the MVITA code are compared to the data obtained.

1 Introduction and background

A hypothetical core melt accident in a light water reactor (LWR) may result in accumulation of core debris in the lower head of the reactor pressure vessel (RPV). The core debris, if unquenched, may heat up and commence natural circulation. The core melt pool formed likely will consist of a decay-heated oxidic region at the bottom and a metal layer on the top. The thermal loadings exerted on the vessel wall by the naturally circulating pool have been a subject of study for the last several years, see e.g. [1]. The primary interest has been the determination of the feasibility of the accident management scheme of retaining the melt within the lower head by cooling the vessel outside wall with water.

Much has been learned since the focused studies began. An evaluation of the in-vessel melt retention management scheme for the AP-600 was performed by Theofanous et al. [2], who found sufficient margin for the critical heat flux for heat removal at the vessel outer wall, over the thermal loading imposed by the circulating melt inside the lower head. The metal layer resident on top of the oxidic pool was found to focus the heat added to it from the oxidic pool towards the vessel wall. However, for the AP-600 geometry and scenario, it was found that the metal layer would be quite thick and the focused heat flux at the vessel wall was lower than the critical heat flux at the vessel outer wall.

The AP-600 evaluation was based on data obtained from the COPO [3], UCLA [4] and the mini-ACOPO [2] experiments, employing water, freon and water, respectively as melt simulants. The mini-ACOPO experiments also employed the heat capacity of the melt simulant in a transient cool-down mode to obtain the heat transfer data. A reasonable equivalence between the volumetric heating and the transient cool-down has been demonstrated through CFD analyses [5].

Experiments and analyses have been continuing since the evaluation performed for the AP-600. The mini-ACOPO experiments have been transformed into ACOPO experiments, employing a one-half scale 3-D representation of the lower head; again employing water and the transient cool-down technique. The COPO facility has employed top and side wall cooling to create a crust (ice), i.e. a truly isothermal boundary [6]. The BALI experiments [6], conducted in Grenoble, have employed a full scale 110^o slice facility, with water as melt simulant, also cooled at top and side wall to create an ice crust boundary.

The RASPLAV Program [7], conducted in Russia, employs prototypic (UO_2-ZrO_2) melt materials in a 200 kg slice facility, in which the thermal loadings imposed by the prototypic melt on a cooled vessel wall are measured. Two tests have been conducted so far, for which data is being analyzed. In addition, the RASPLAV Program has also employed a salt test facility in which experiments with eutectic and non-eutectic salt have been conducted. The data in some of the tests have been analyzed, while others need further analysis.

A separate-effect experiment [8] on the focusing effect of the metallic layer has been performed at the BALI facility. This experiment employed water as the metal-layer simulant. A focusing effect of $\simeq 2.0$ was found, which increased to $\simeq 6.0$ for very thin layers (aspect ratio of $\simeq 1/40$).

We believe the recent changes in the situation with respect to the prediction of the thermal loadings on the vessel wall, and with respect to the feasibility of the in-vessel melt retention may be described as follows:

- The RASPLAV experiments, conducted at $Ra' \leq 10^{11} - 10^{12}$, have shown corium melt stratification for prototypic compositions and temperatures. The interpretation of the data obtained with respect to stratification has not been completed so far. If the stratification is found to be stable, and prototypic, for the accident composition and temperatures, it may affect the natural circulation flow fields. The magnitude of the effects of stratification at the prototypic Ra' numbers (when the flows would have greater turbulence than for those in the RASPLAV tests) has not been determined.
- The measured values of the Nu_{up}, Nu_{dn} and Nu_{sd}, obtained from the recent isothermal-boundary COPO and BALI experiments, appear to be larger than those obtained from the ACOPO facility, which did not have crusts at the boundaries. These measured values are also larger than those derived from the Steinberner and Reineke correlation. The Ra' number scaling, however, holds. These differences may be due to the changes in the boundary layer heat transfer at the crust boundary, or due to the change in the thermal expansion of water at +4°C. Resolution of these differences has not been achieved so far.
- The salt experiments performed in the RASPLAV Program have also shown some differences in the heat transfer at the boundaries of a naturally convecting pool with or without crust boundaries.

- The metal layer resident on top of a heat generating oxidic material pool was found to focus the heat, received by it, towards the cooled side wall of the vessel; thereby indicating that the vessel corner may be the most failure-prone location. This has been confirmed by separate-effect tests.

  However, evaluations employing integral two-dimensional analyses of the oxidic pool, metal layer and vessel have indicated a significant amelioration of the peaking of heat flux at the vessel location next to a thin metal layer.

We believe that the recent changes have introduced uncertainties, which may not allow a straight-forward evaluation of the feasibility of in-vessel melt retention for a severe accident in reactors, with high power densities, in which thin metal layer could be formed and oxidic melt stratification could occur. Currently there are no integral experiments, employing either prototypic or simulant materials, modeling the prototypic integral situation of an oxidic pool and a metal layer, which can support such evaluation. We, therefore, believe that the SIMECO test program, described in the following paragraphs, employing:
- eutectic and non-eutectic binary salt mixture melts to represent crusts and crusts with mushy regions, respectively,
- turbulent natural convection flow fields,
- stratified melt configurations with different density salt mixtures,
- appropriate molten metals to represent metal layers,
- different boundary conditions,
- key parameter variations,

performed as step by step integral experiments will provide a valuable data base for the evaluation of the in-vessel melt retention as an accident management strategy for high power reactor of the EPR scale.

The specific objectives of the experiments in the SIMECO facility are to investigate (i) the effects of boundary crusts and mushy layers on natural convection heat transfer; (ii) the effects of melt stratification on natural circulation; (iii) the amelioration of melt stratification by turbulent flow fields, and finally (iv) the multidimensional heat transfer in, and between, the melt pool, the top metallic layer and the vessel. The data base obtained will supplement those obtained in the RASPLAV test facilities.

2 SIMECO facility and experimental program

Experimental simulation is performed in a slice-type facility which includes a semicircular section and a vertical section; Fig.1. Diameter, height and width of the test section are 530x620x90mm. Brass is used as the slice walls, except for the front wall. The vessel wall is represented by a 23-mm thick brass plate. The front wall is made either of special glass for flow and crust visualization, or, of a thin copper sheet for infrared thermovisualization. Two water cooling loops with controlled flow rates are used for cooling the vessel wall; Fig.2. Water temperature measurements are used to obtain the average heat flux data on the side walls. In addition, up to 36 K-type thermocouples are built in the brass vessel wall at different angles and locations. Measured temperatures are then used to derive local heat fluxes.

Binary salt mixtures are employed as melt simulant. Both eutectic mixture (50%-50%) and non-eutectic mixture (20%-80%) of $NaNO_3$-KNO_3 are used in the SIMECO experiments.

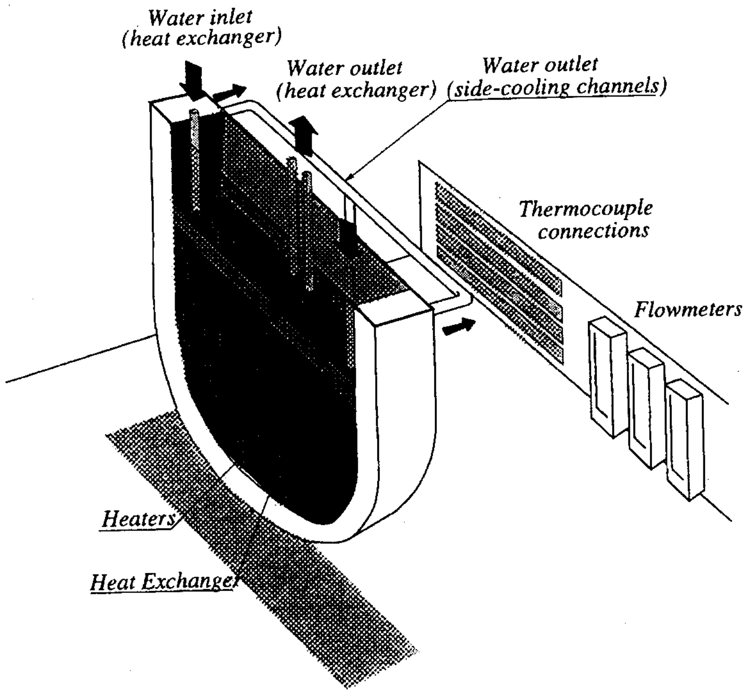

Figure 1: SIMECO experimental facility - overview.

The binary-mixture phase diagram is quite similar to that of the binary-oxide core melt UO_2-ZrO_2. For the 20%-80% mixture the temperature difference between the liquidus and solidus is about 60K. Liquidus temperatures of the binary mixture are 220°C and 280°C for the 50%-50% and 20%-80% compositions, respectively. Previously, these salt mixtures were extensively, and successfully, employed as core melt simulants in melt-vessel interaction experiments performed at RIT/NPS [6]. The heat of fusion, heat capacity, density, viscosity, heat conductivity of these mixtures were measured to enable pre-test and post-test analyses of the experiments.

Metallic layers of different thickness can be located on top of the salt mixture pool. A thin and highly-conductive copper sheet is used to separate the two layers. Lead-bismuth alloy or cerrobend alloy are employed as the simulant fluid of the molten steel layer.

Several heat exchangers are employed to provide the upper boundary cooling condition. Control of the water flow and measurement of water temperature in the different heat exchangers enable determination of the local distribution of upward heat fluxes either on the upper surface of the melt pool in case without metal layer, or on the upper surface of the metal layer otherwise.

Inside the slice up to 36 K-type thermocouples are installed to measure the local temperature variations in the liquid pool and in the metallic layer. Emphasis is placed on the near-wall region to detect the crust existence. In total, up to 96 measuring channels can be simultaneously employed in the RIT/NPS data acquisition system using a HP-1300A mainframe.

Internal heating in the binary-salt melt pool is provided by thin wire-type heaters. Two heaters, 3-mm in diameter and 4-m long are uniformly distributed in the semicircular section. They can supply up to 4 kW of heating to the molten salt pool.

The SIMECO test matrix is designed to cover:
(i) different heat generation rates and different top and sidewall cooling conditions, and
(ii) variation of metallic layer thickness (thin, intermediate, and thick).

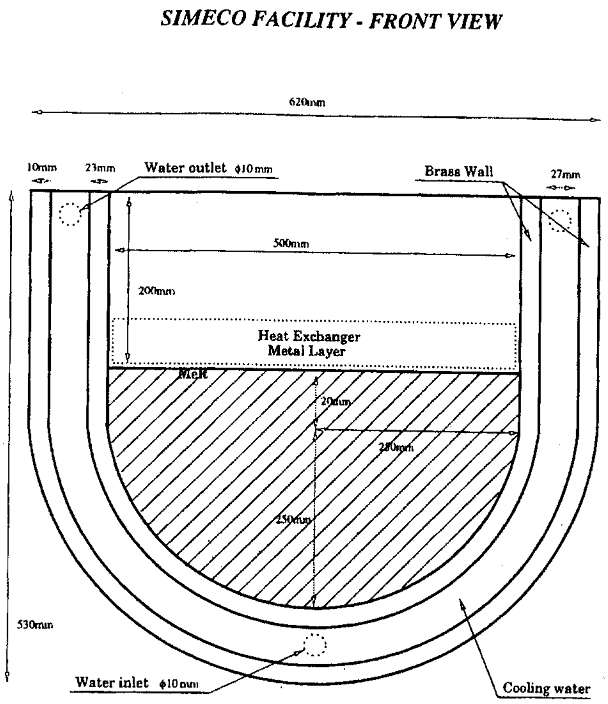

Figure 2: SIMECO experimental facility - dimensions.

In a scoping test series, water was employed as melt simulant, while in the main test series, binary salt mixtures are employed. The SIMECO facility enables experiments with Rayleigh numbers up to $1.5 \cdot 10^{13}$ (with salt) or $3.2 \cdot 10^{13}$ (with water) for the pool natural convection and up to 10^8 for the metallic layer natural convection. The flow fields are expected to be turbulent for these values of the Ra'.

3 Experimental results and analysis

The SIMECO data base acquired so far is preliminary, since the experimental equipment operation and instrumentation is still being improved. The experiments performed so far include (i) mini-SIMECO experiments, using both eutectic and non-eutectic melts, (ii) SIMECO experiments, using water as working fluid, and (iii) the first SIMECO test series in which eutectic binary salt was employed as a melt simulant.

3.1 Mini-SIMECO test series

The mini-SIMECO test series was performed in a test facility similar to that described in the previous section, but smaller and much simpler. The main purpose of the mini-SIMECO program was to examine the technical problems for building the SIMECO facility with internal heaters. Nonetheless, the mini-SIMECO test series provided useful data on melt pool formation and heat transfer. In particular, visualization of the melt pool formation dynamics was obtained. The crust was found thickest at the lowermost region of the pool, while the top crust and the crust at the pool's corner were very thin. More importantly, analysis of the mini-SIMECO test results revealed, that for the longer-term transients of melt pool formation and heat transfer; the heating method used (i.e. internal heaters) provides good simulation of the volumetric heat source. This is valid because the time scale of convective heat transfer from the heater's surface to a given control volume is much smaller than the time scales of either melt pool formation or transient heat up. Additionally, while the energy transfer rate is important, heat transfer processes in a particular control volume in the pool are indifferent to the way in which the heat was generated in other parts of the pool.

3.2 SIMECO water test series

The SIMECO water test series was conducted to test the performance of the water cooling circuit, heaters, thermocouples and DAS.

In this test series, truly isothermal boundary conditions were not provided on the pool boundaries. The vessel semicircular wall adapted itself to the heat fluxes. Nonetheless, very good mixing was observed in the pool's upper region, with heat fluxes peaking at the pool corner. Figs.3-4 depict experimental results of the SW-4 test, in which 3.7 kW was delivered to the water pool by the wire heaters. The pool's Rayleigh number reached $Ra' = 3.14{\cdot}10^{13}$. Upward and downward Nusselt numbers were estimated from measured data as $Nu_{up} = 476$ and $Nu_{down} = 209$. The upper Nusselt number is close to that determined from the Steinberner-Reineke correlation [12] and the new BALI correlation [6].

3.3 SIMECO eutectic-salt test series

Six experiments were conducted in this series. This section focuses on results and analysis of SSEu-3 test, in which a molten-salt pool was formed during the mixture heat up and re-melting processes. Approximately, 3.7 kW was supplied to provide $Ra' = 1.51{\cdot}10^{13}$. Results of the SSEu-3 test are presented in Figs.5-7. The transient heat up and melt pool formation occurred in about 2 hours. At the steady state the molten salt pool reached relatively high temperatures (more than 280°C, i.e. 60K superheat). Highest vessel temperature and heat fluxes were measured in the pool corner (at angles of 80°-90° degrees). Upward heat fluxes of 15.5 and 17 kW/m^2 were obtained from thermocouples and flow measurements in the two upper heat exchangers. Water temperatures were $\simeq$ 8°C at the inlet and 12°C at the exit from heat exchangers. Measurements of the local upward heat flux distribution was attempted, but flow leak between the sections of the heat exchangers affected the results.

Modeling of the heat transfer processes in the SIMECO facility is performed by the MVITA code developed at RIT/NPS. MVITA models the melt heat-up and natural circulation phases with an energy equation in which equivalent conductivity and convectivity are introduced. MVITA assumes that the heat flow is carried to the pool upper surface by the fluctuating part of the upward turbulent velocity. This velocity in the prototypic scenario is very small, i.e. about 1-5mm/sec. The heat transport to the side wall is assumed to be across a boundary layer at the wall. The heat transfer in the boundary layer is given by an Eckert type correlation. The MVITA model has been verified against several measurements. It should be noted however that the data base on which the MVITA model was validated includes melt pool or fluid layer experiments with isothermal boundaries, but not frozen boundaries. Frozen boundaries were realized in COPO-II and BALI experiments. However, only in the SIMECO facility, processes in the vessel lower head are experimentally modeled in an integral fashion, i.e. including melt pool, crust, vessel wall and molten metal layer.

.Calculated results for the SIMECO SSEu-3 test with the MVITA model, are shown in Figs.5-8. It can be seen that the major trends in the vessel wall heat flux and temperature can be predicted by the MVITA model. The analyses performed indicated that a gap may have formed between the top heat exchanger and the salt pool, causing additional thermal resistance and modifying the top thermal boundary condition of the pool. Modifications of the SIMECO facility are being performed to ensure complete contact between the heat exchanger and the salt pool. Additional experiments in this test series will be performed to obtain and enlarge the data base.

4 Concluding remarks

Design and construction of the SIMECO facility has been completed and the first experimental series was performed. Turbulent natural circulation flow conditions are realized in the SIMECO tests, however the Ra' values achieved are much lower than those in the prototypic accident conditions and geometry. So far, 16 experiments were conducted: 10 with water and 6 with eutectic salt as melt simulants. A new experimental data base is being obtained.

In the 1998 year, other series of the SIMECO experiments will be conducted, with metallic layers with melt stratification and with non-eutectic salt mixture. Results of these experiments will be compared to the data reported here. After that the brass vessel will be replaced by a melt-able vessel to provide data pertinent to prototypical scenarios in which vessel melting is predicted to occur. The MVITA model includes description of vessel melting and will be validated with the data obtained.

We believe that the SIMECO facility will provide the integral data base which will delineate the effects on the vessel thermal loading of crust boundaries, of phase chang, of melt stratification and of the focusing of heat by the metallic layer.

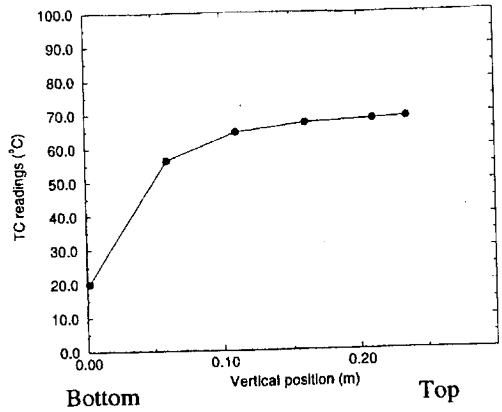

Figure 3: SW-4 test: centerline temperature in the pool.

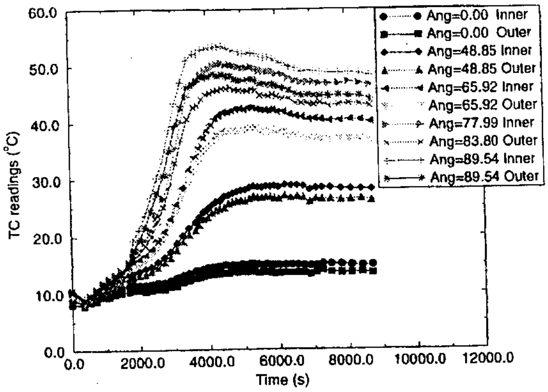

Figure 6: SSEu-3 test: transient temperature in the vessel wall.

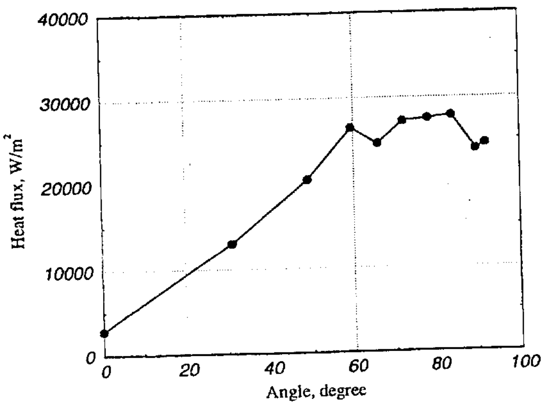

Figure 4: SW-4 test: heat fluxes in the vessel wall (determined from thermocouple readings).

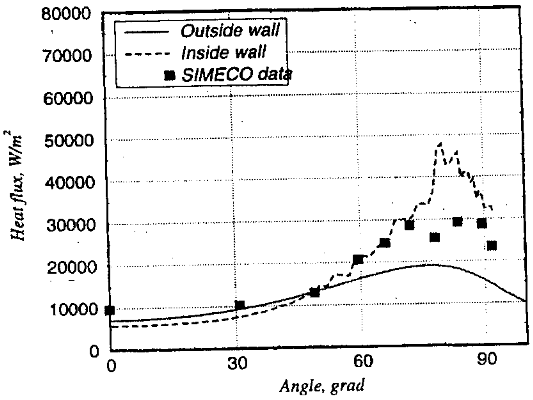

Figure 7: MVITA calculated results versus the SSEu-3 test results for the vessel wall heat fluxes, determined from thermocouple readings.

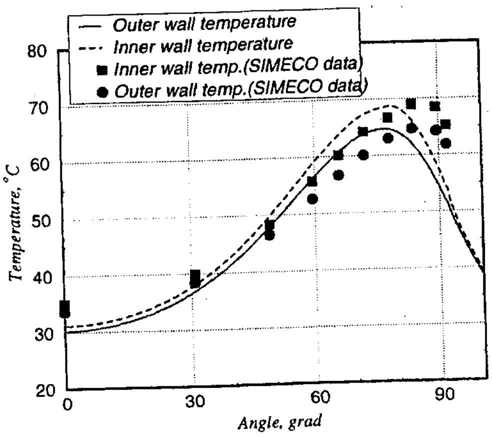

Figure 5: MVITA calculational results versus the SSEu-3 test results for temperature in the vessel wall.

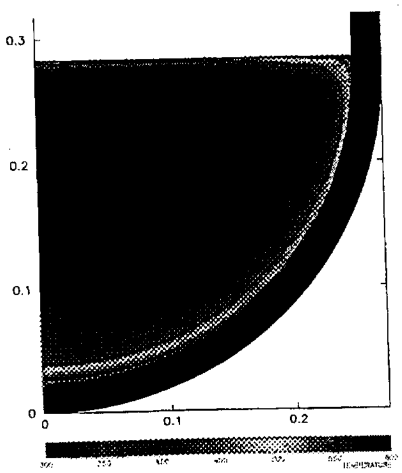

Figure 8: MVITA prediction of the SIMECO SSEu-3 melt pool.

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