Rasplav Application Report
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Application of the OECD Rasplav Project Results to Evaluations at Prototypic Accident Conditions

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1. Background

The concept of arresting the progression of a severe accident in the vessel of a medium power light water reactor (LWR) by external cooling of the vessel has been recognized as an attractive accident management measure. In-vessel retention of molten corium would halt the accident progression and eliminate the threats to containment integrity due to the ex-vessel phenomena.

The integrity of the lower head may be threatened during the high-temperature transient phase of a severe accident by phenomena related to corium relocation, steam explosions, jet impingement, etc. Furthermore, formation of a large molten pool in the lower head of an externally cooled vessel would create a large thermal gradient across the vessel walls.

The concept of in-vessel retention by external cooling has been investigated for the Loviisa pressurized water reactor (PWR) in Finland[1,2,3], and accepted as the major accident management measure by Finnish regulatory authority STUK. In the USA, the design of the advanced passive reactor AP600 employs reactor ex-vessel flooding as an accident management scheme[4,5]. The in-vessel melt retention concept has also been investigated for the Zion PWR[6,7,8], boiling water reactors (BWR)[9] and CANDU reactors[9a,9b,9c]. There are also new plant designs based on the passive safety systems, for which in-vessel retention is being studied as a key accident management strategy. Such designs are Russian VVER-640 and German SWR-1000 as well as Westinghouse EP1000 in co-operation with European utilities.

The main focus for these studies has been the thermal loading imposed by the core melt on the reactor pressure vessel (RPV) lower head. The objective has been to determine whether the imposed heat flux would exceed the heat removal capability (critical heat flux) on the external surface of the vessel, and to assess the pressure bearing capability of the vessel wall subjected to thinning from inside and to a high thermal gradient by external cooling.

Experimental programs performed at various facilities also supported these studies. The COPO experiments[10], conducted in Finland, provided data for the variation in heat flux with the azimuthal angle for a half-scale slice representation of the torospherical (VVER-440 vessel model) and hemispherical lower head. The isothermal upper boundary conditions were applied as a rule, and crust formation has been also modeled in these experiments[11].The French have employed the BALI facility[14], which is a full-scale slice geometry representation of the spherical lower head of a French PWR. The UCLA experiments[12,13] were performed on a much smaller scale than the COPO and BALI facilities, using a three-dimensional vessel head. The University of California, Santa Barbara (UCSB) experiments were performed on the mini-ACOPO and ACOPO facilities[15,16]. The mini-ACOPO was built to demonstrate the efficiency of the technique. The ACOPO facility is a half-scale three-dimensional hemispherical model employing the transient cooldown technique to obtain data on the heat fluxes imposed on the vessel wall by a heat generating fluid. The COPO, BALI and ACOPO provided data for the high Rayleigh numbers that are prototypical for the reactor conditions.

In most of the above experiments, volumetrically heated water was used as the simulant fluid (in case of the ACOPO facilities volumetric heating was simulated with slow transient cooldown; UCLA and mini-ACOPO facilities used also freon as a simulant). More recently, molten salts have been used to simulate molten corium in the OECD Rasplav Project, and also in the SIMECO facility[17] at the Royal Institute of Technology (RIT), Sweden.

In addition to experiments to allow modeling of the heat flux on the inner surface of the vessel, experimental programs have been also conducted to investigate the critical heat flux for the boiling process initiated on the *outer* surface of the vessel due to cavity flooding (external vessel cooling). The ULPU facility was originally constructed at UCSB[3,18] to model the Loviisa-specific boiling conditions and later it was extended to provide virtually full-scale critical heat flux data to support the AP600 studies. Critical heat flux distribution was measured in a small-scale downward facing hemispherical surface at Penn State[19]. The CYBL facility at Sandia National Laboratories used a full-scale vessel to study boiling on the exterior surface of a torispherical lower head[47]. The SULTAN facility[20] at Grenoble provided critical heat flux data for inclined flow channels, and the Gidropress design office has investigated the critical heat flux for VVER specific flow paths in Russia[44].

The key distinguishing feature of a large self-heated pool or molten corium in the lower head of an LWR vessel is natural circulation at very high internal Rayleigh numbers (10^{15}-10^{17}). The flow is turbulent and the heat flux imposed on the vessel wall varies greatly over the azimuthal angle. The COPO[10] experimental data for fluids with Rayleigh numbers of 10^{14}-10^{15} were the first to convincingly show that the heat flux is very low at the bottom part of the head, and rises to substantial values at higher levels within the reactor pressure vessel. Fortunately, the heat removal capability, due to boiling on the outer vessel surface, has also been found to vary in the same fashion. Thus, if the reactor vessel integrity could be preserved during the relocation phase, and if the rate of heat removal by external cooling was substantially greater than the thermal loading at the lower head after the molten pool formation, the concept of in-vessel retention would seem feasible.

Thermal hydraulic studies of the melt pool behavior assuming that a molten metal layer could form on top of the underlying oxidic corium were performed. The heat-focusing effect of this molten metal layer is of concern, because the vessel walls adjacent to the metal layer are subjected to increased heat fluxes, which could lead to substantial localized melting of the walls. Scoping calculations have also confirmed that shallow metal layers may produce heat fluxes at the adjacent walls that exceed the critical heat flux.

Since in-vessel melt retention has become an important safety objective for medium power reactors, it is important to evaluate and model the relevant phenomena that will contribute to melt retention under prototypical accident conditions. At the same time, even if not aiming at in-vessel retention, there is a clear need to understand the convective molten pool behavior, since melt pools have important implications on the core relocation and the RPV failure mode that both, in turn, have further consequences on the accident behavior. It is necessary to determine the uncertainties introduced by using experimental data, or correlations derived from these data, to model the in-reactor situation. Most of these uncertainties arise from differences between the experimental and in-reactor conditions: (i) use of simulant fluids, such as water and molten salts; (ii) differences in boundary conditions; (iii) differences in the mode and/or uniformity of heating; and (iv) differences in geometry.

2. Overview of the Rasplav project

The basic objective of the Rasplav Project is to provide data on the behavior of molten core materials on the RPV lower head under severe accident conditions, and to assess the possible physicochemical interactions between molten corium and the vessel wall. Data is also obtained to confirm heat-transfer modeling for a large convective corium pool within the lower head. The project consists of the following components:

(i) providing data from large-scale integral experiments on the behavior and interactions of prototypic core-melt materials within the lower head;

(ii) performing small-scale corium experiments to measure the thermophysical properties (density, electrical and thermal conductivity, viscosity, etc.) required for performing and interpreting the integral (large-scale) tests;

(iii) determination of the uncertainties introduced by using non-prototypic conditions and materials in the small-scale corium experiments;

(iv) performing the molten-salt experiments with the following objectives:

- to study heat transfer processes in the melt;
- to justify the choice of procedures for large-scale experiments, such as the method of heating;
- to develop an understanding of relevant phenomena, such as crust formation, and non-eutectic materials behavior;

(v) development of computer tools and models for analysis of results from the large-scale integral tests and the supporting small-scale experiments.

During the first phase of the Rasplav Project (1994-97) the large-scale experiments demonstrated clearly that behavior of corium melts differed from that of simulant materials. Under certain conditions, the corium would separate into two layers that were enriched in Zr or in U.

The second phase of the Rasplav Project started in July 1997 and it concentrated on exploring the physical and chemical phenomena occurring in a convective molten pool, such as the effect of differing corium compositions, the potential for and effects of material stratification and the influence of various boundary conditions.

The work involved a combination of integral and separate effect tests, including (i) molten-salt tests to investigate non-eutectic mixtures, and (ii) extension of the material property data base to allow interpretation and modeling of the experimental data.

The Rasplav corium pool experiments cannot fully simulate the real in-reactor situation, in particular not in the following respects:

1. The internal Rayleigh number for melt circulation in the Rasplav tests is 10^{11} to 10^{12}, whereas that for prototypic accident conditions is 10^{15} to 10^{17}. This difference is primarily due to the smaller scale of the Rasplav experiments. Hence, the Rasplav natural convection flows are predominantly laminar, while highly turbulent flow may occur under prototypic conditions.

2. The Rasplav experiments have semicircular slice geometry**,** whereas the lower part of a PWR reactor vessel has a hemispherical geometry. The Rasplav geometry was chosen to maximize the Rayleigh number for the specific mass of corium employed.

3. The melt is heated through the inductively heated sidewalls, rather than by volumetric heating. This was necessary because the electrical resistivity of molten corium is too low to allow satisfactory Joule heating, and because any layers of separated metallic material could lead to short circuits.

4. The upper boundary condition in the Rasplav experiments differs from the isothermal conditions that may exist on the upper pool boundary in an in-reactor situation.

A set of experiments with binary and ternary molten salts has also been performed within the Rasplav Project to complement the corium experiments. The molten-salt experiments had two objectives. The first one was to investigate the effects of non-prototypic conditions in the Rasplav corium experiments, such as the use of side-wall heating, and the existence of non-isothermal conditions at the upper pool boundary. The second objective was to obtain further data with simulant materials that exhibit phenomena such as crust formation (eutectic salts), a large solidus-liquidus temperature difference (non-eutectic salts) and a prototypic Prandtl number (ternary salt mixtures).

The primary objective of the material-properties measurements is to evaluate the key thermophysical properties (electrical and thermal conductivity, viscosity and density of corium mixtures) required for performing and interpreting the integral tests.

The objectives of the code development activities were to develop the codes that are capable of simulating relevant in-vessel phenomena. These codes were then applied to pre- and post-test analysis of the corium and molten salt experiments and to the analytical support of facility design and test methodology. The success of the developed methods was demonstrated with accurate pre-test predictions, which played a key role during the test performance.

3. Rasplav Project Operations

Four large-scale (~200kg of corium) integral tests were performed with prefabricated (prototypic) corium. Use of prefabricated corium allowed the assessment of many phenomena that could not be adequately simulated by molten salts. They included the impact of corium composition on the extent of molten pool convection and on thermal hydraulic behavior, the formation of a mushy region (due to incongruent melting at the pool boundaries) and crust.

The corium compositions were chosen to represent likely in-reactor compositions. During early feasibility studies, it was found that the electrical conductivity of molten corium was too high to allow direct electric heating (Joule heating) to be used as a method for simulating decay heat. Hence, the choice was made to employ heating from the inductively heated sidewalls. The technical achievements from this part of the program include the development of protection techniques for the heaters and steel walls, allowing long term retention of the melt at temperatures of 2500 – 2650°C. These techniques will be important for the design of future experiments in the Rasplav Project or elsewhere.

Corium compositions based on UO_2-ZrO_2-Zr mixtures, with a U/Zr atomic ratio of 1.6, were chosen to represent corium that is expected to be predominant in the late phase of a severe accident. Since the corium mixture was to be heated from the sidewalls, this required that the mixture should also have a relatively high thermal conductivity. Three different corium compositions were considered for these tests with varying degrees of zirconium oxidation (Table 1).

The thermal conductivity of a corium melt depends significantly on the melt oxygen content (i.e., on the Zr/ZrO_2 ratio in the starting materials). Hence, the corium batch of about 200 kg employed in the first and second large scale tests was formulated as 81.8 wt.% UO_2, 5.0 wt.% ZrO_2, 13.2 wt.% Zr . This mixture composition, designated C-22, corresponds to oxidation of 22% Zr to ZrO_2. It is, perhaps, at the lower end of prototypic PWR corium compositions, because a core melt accident implies a high degree of Zr oxidation. It has been proposed that the C-22 mixture could be more representative of BWR and CANDU corium, since there is a much higher proportion of Zr in BWR and CANDU cores. Steam starvation could effect the high-temperature accident progress in these reactors.

Table 1: Matrix of Corium Compositions Studied

Corium composition	Zirconium oxidation (%)	Composition (mol. % / wt. %)			Content wt.%	U/Zr ratio
		UO_2	**ZrO_2**	**Zr**	**C**	
C-22	22	62 / 81.8	8.4 / 5.0	29.6 / 13.2	0.3	1.6
C-50	50	62 / 80.4	19 / 11.3	19 / 8.3	0.1	1.6
C-100	100	62 / 78.1	38 / 21.9	-	0.01	1.6
C-32	32	54.5 / 76.2	14.5 / 9.3	31.0 / 14.5	0.04	1.2

The first two tests were performed with a C-22 corium composition. The stratification of the corium to two different layers was observed in these experiments.

The third test was performed with a C-100 corium composition of 78.1 wt.% UO_2, 21.9 wt.% ZrO_2**,** corresponding to full Zr oxidation**.** This test fulfilled the requirement of having one test with a melt composition similar to that found in the lower head after the TMI-2 accident. The C-100 corium melt has a very low thermal conductivity and a much higher liquidus temperature. Therefore it had to be diluted with 1.8 wt.% La_2O_3 (representing fission product oxides) and 1.2 wt.% FeO to allow the test to be performed. Unfortunately, the use of FeO mixed with La_2O_3 led to operational problems in the third test (see Section 4.1).

The fourth test was performed with reduced ratio of U/Zr to 1.2 and increased oxidation rate of zirconium to 32%. Another major difference from previous experiments was significant reduction of carbon content. The decrease of carbon content was necessary in order to prevent the segregation found in the first two large-scale experiments that was traced to be due to the carbon. The U/Zr ratio was decreased to bring the composition into the area of the predicted miscibility gap and to prevent significant interactions of zirconium with the tungsten.

The Rasplav series of molten-salt tests have produced high-quality data that have served to complement the corium test data. The tests with binary salt mixtures have been performed with both sidewall and internal heating to study the differences in melt behavior caused by sidewall heating (as used in the corium tests). The heat transfer results obtained using the two heating methods were found to agree and they were, within measurement errors, identical. Moreover, two series of experiments were performed using non-eutectic salt composition to study heat transfer phenomena and crust formation from complex mixture. These unique data were used to validate the crust formation models. Although previous salt tests have not employed cooling at the pool upper boundary (i.e. an isothermal boundary condition), the new molten-salt facility, recently completed, will be equipped to provide such cooling. This facility will also be used to study melt stratification phenomena.

A large number of small-scale and medium-scale experiments (5-20 kg) with prefabricated corium have been performed to perfect experimental techniques and to obtain data in support of the large-scale tests. These experiments were successful in achieving their objectives and the data is considered to be reliable*. They include measurements of the thermophysical properties for corium C-22, C-32 and C-100, the corium mixtures employed in the large-scale tests. These data are essential for analysis and interpretation of the large-scale test results. Moreover these experiments allowed investigating important phenomena such as stratification, separation of metallic fractions, corium metal interactions and behavior of fission product simulants.

The analytical and modeling activities are important components of the Rasplav Project. The main analytical tools are the two-dimensional and the three-dimensional codes CONV-2D and CONV-3D, developed at IBRAE[21,22]. The CONV-3D code has been used successfully for pre-test simulations and post-test analyses of the large-scale tests.

4. Major findings from the Rasplav project tests and analyses

4.1. Large-scale corium tests

As mentioned above, four large-scale (~200 kg) corium experiments were successfully performed, and valuable experience in test methodology was gained. An important achievement was the preparation of a range of corium batches with predefined composition.

The C-22 and C-100 compositions demonstrated completely different behavior in the large-scale tests. In the first two tests, performed with C-22 corium containing also some amount of carbon that remained in corium due to the corium manufacturing process, the molten pool developed

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* The American Nuclear Society Thermal Hydraulics Division (THD) and the THD Honors and Awards Committee recognized the viscosity-measurement work[48] as the best publication in 1998.

stratification[23,24].This is an exclusive finding from the Rasplav tests, which could not be observed in the simulant material tests. The lower C-22 layer consisted of a molten oxide mixture, while the upper layer was predominantly metallic. The upper layer also contained almost all carbon impurities. This type of stratification was also observed in small-scale and medium-scale tests with a corium that contained carbon impurities. A further small-scale test with a carbon-free corium composition of lower oxygen content produced separation of metallic fractions (leaking of metallic phase) during heating up. However, no stratification was observed during molten conditions.

Earlier material and chemistry research has also identified the possibility of corium stratification and the presence of high-temperature miscibility gap in the U-Zr-O system[25]. It is interesting to note that later investigations found no evidence of a miscibility gap[26]**.**

Thermodynamic calculations[27] and experiments with small oxygen content[28] indicated that the observed stratification could be potentially caused by a miscibility gap in the U-O-Zr system that could cause the molten corium to separate into two immiscible liquids at elevated temperatures. If the effect of 0.3 wt.% carbon on the miscibility gap is supposed to be negligible, the mass ratio between the phases as well as the composition and temperature of the phases do not support the hypothesis of separation being due to a miscibility gap in the first two large-scale Rasplav tests, as shown in Ref. 29. However, the extent of the U-Zr-O miscibility gap is not precisely known. Therefore a specific series of small-scale tests was performed and the results suggested that typical corium compositions should lie outside the range of immiscible compositions.

Currently, the stratification is believed to be due to the presence of carbon. However, it is not yet clear that this is the only parameter influencing the stratification and the possible mechanism proposed in Ref. 29 should be discussed at the light of recent investigations[51]. Separation observed in the series of supporting tests and in the last large-scale tests was caused by relocation of metallic material downward through the gaps between briquettes.

The results of the large-scale integral tests indicate that the extent of corium stratification depends on the residence time at high temperature. For example, in two tests (AW-200-1 and Tulpan T3), the upper layer rich in metallic Zr had a density ~15% lower than that of the underlying U-rich and oxygen-rich layer, and occupied ~20% of the total melt volume. In a further test (AW-200-2), however, there was insufficient time for the separation process to reach equilibrium, and the upper metal-rich layer occupied a much greater volume fraction. These observations are important because the extent of corium stratification during a reactor accident could have a significant impact on the heat flux distribution.

In many experiments with C-22 corium, traces of metallic uranium were observed in the post-test melts. In the pole of test wall of AW-1:2.5, interaction of metallic Fe-Zr-U phase with the steel test wall caused penetration of the wall to a depth of ~5 mm by formation of low temperature eutectic compositions.

The third integral experiment, AW200-3, was performed using C-100; i.e. fully oxidized corium mixed with 1.2 wt.% FeO and 1.8 wt.% La_2O_3 to lower its melting point. However, due to the interaction between Fe and the tungsten protector, the upper part of the test-section wall was damaged and 22 kg corium leaked. The Rasplav team and PRG (Programme Review Group of the OECD Rasplav Project) believe that fully oxidized U-Zr-O corium behaves as a single-phase liquid, and that there is no need for further integral experiments with this corium composition.

The similar behavior of the melt pool was found in the fourth test. Although the corium composition contained only 32% of oxidized zirconium, metallic materials in the form of $(Zr_{0.98}U_{0.02})O_{0.3\text{-}0.4}$ relocated downward caused increase of U/Zr ratio in the bulk corium from initial value 1.2 to the value of 1.4. The molten pool was highly uniform that was confirmed by sampling of molten corium during the test. In addition, the solidification process was found to be responsible for the change of composition during cooling down phase. A quantitative calculation of the variation of the U/Zr ratio has been achieved recently, based on the Scheil-Gulliver solidification model and GEMINI calculations, which shows quantitative agreement with the measurements[51].

4.2. Medium-scale and small-scale experiments

A series of tests have been performed in the medium and small-scale facilities Tulpan, TF, STF, etc. (see attached bibliography) to investigate the possible occurrence of stratification in U-O-Zr-Fe melts. The objective of these tests was to study the effects of convection, rapid quenching, and the presence of additives on layer development.

Some tests were conducted in Tulpan T4 with fully oxidized material (UO_2+ZrO_2), which is believed to form a single-phase liquid at high temperatures. Nevertheless, the post-test corium showed a non-uniform U/Zr distribution, which has been interpreted as a consequence of post-test cooling. These tests have also been used to validate thermodynamic data bases.

In high temperature tests using corium doped with FeO and La_2O_3 additives, the FeO was reduced to metallic Fe, which attacked the tungsten protectors. In contrast, lanthanum oxide was uniformly distributed throughout the oxygen-rich melt phases. Such behavior of iron may be caused by the specific loading of additives used as it was noted later[30].

Tests have also been performed to investigate the interaction kinetics of molten Zr/Fe mixtures with steel container walls as a function of the melt Zr/Fe ratio[31] for the temperature range up to 1300^{o}C.

4.3. Material Properties

Electrical conductivity values of different corium compositions have been measured over a wide temperature range (temperature up to 2800^{o}C)[32]. The conductivity of oxygen-rich corium compositions was shown to increase significantly by the onset of melting, making direct electric heating difficult to control for a partially molten pool.

Thermal conductivity values of different corium compositions have been measured at temperatures up to 2800°C. Conductivity was found to depend significantly upon metallic zirconium content (zirconium oxidation)[33].

Viscosity measurements revealed that the dependence of viscosity upon zirconium oxidation is weak[34].

The viscometry method was also used to measure solidus and liquidus temperatures.

Surface tension[45] and the density[36] for different corium compositions were also measured.

4.4. Salt Experiments

A eutectic salt mixture (8NaF-92$NaBF_4$) was used to investigate the effect of different heating methods (direct, i.e. Joule heating vs. sidewall heating) and of crust formation on heat transfer across the test-section wall, simulating the lower vessel head. The results of these experiments indicated that, within the limits of experimental uncertainty, both heating methods produced a similar heat transfer distribution.

Two series of tests have also been performed with a non-eutectic salt mixture (25NaF-75$NaBF_4$). These were the first tests to investigate the effect of the transition zone between solidus and liquidus on heat transfer, and have provided valuable data for modeling the temperature distributions within the transition zone and at the interface between crust and liquid[46]. The results were recently interpreted by CEA[37] and IBRAE[38], and a methodology was developed to describe the interface condition between the solid layer and the liquid**,** based on a thermochemical solidification model. The model predicts that the interfacial temperature between the liquid and solid phases in a high temperature oxygen-rich corium will be equal to the liquidus temperature of the <u>residual</u> liquid, which for the relevant cases of in-vessel retention is close to the liquidus temperature of the <u>overall</u> melt (since the solid fraction is small). Post-test analysis performed recently showed that quasi-steady-state crust formation model can be applied to the analysis and interpretation of experimental data.

4.5. Code Development

During the Rasplav project, the CONV-2D and CONV-3D codes have been developed and distributed to all project participants. These codes use a computational approach, based on two-or three-dimensional fluid dynamics, to simulate the complex heat transfer processes occurring between the major Rasplav vessel components (graphite-plate heaters, tungsten protector, thermal insulation and externally cooled test wall). The codes also include a model for the melt crust and a simple viscosity-based model for the transition region, and take account of the temperature dependencies of the relevant material properties. The applicability of the codes is limited to single-phase fluids with $Ra' \leq 10^{14}$.

Both codes have been extensively validated against the results of molten-salt tests to ensure that the phenomena of interest are modeled satisfactorily. The codes gave good heat transfer predictions for tests using either sidewall heating or volumetric heating, and also for melt configurations where a crust had formed along the externally cooled wall[39,40].

Application of the codes to the corium Rasplav-AW facility design provided valuable information that was used in preparing and performing the tests. The codes successfully predicted the qualitative behavior of the melt, allowing the test procedures to be optimized. Pre-test analysis by the CONV-3D code made for the AW-4 test provided qualitative and quantitative agreement with the data obtained from the last corium tests.

The CONV-2D and CONV-3D codes have not, so far, incorporated a stratified melt pool model because the stratification process is not well understood. Nevertheless, both codes are in the process of being modified by inclusion of coupled thermal hydraulic and chemical models that may be able to describe the stratification observed in the large-scale Rasplav tests.

5. Application of the Rasplav project results to prototypic accident analysis

The objective of the Rasplav large-scale molten corium experiments was to study and evaluate the behavior of a large convective corium pool. In spite of the use of prototypic materials and relatively large scale, the obtained test results cannot be directly applied to evaluation of severe accident scenarios. The full analysis of the molten corium behavior includes in addition the results from many various test programs that have studied in detail the heat transfer mechanisms in the heat generating fluids:

- the high Ra' number water experiments from the COPO and BALI facilities using a large-scale slice geometry, including those recently performed with frozen boundaries;
- the experiments at the UCLA facility, and the cooldown experiments at the mini-ACOPO and ACOPO facilities, using hemispherical geometry;
- the Rasplav experiments with eutectic and non-eutectic salt mixtures;
- the small-scale and medium-scale Rasplav corium melt experiments;

- the integrated salt experiments (including a metal layer) being performed at the SIMECO facility.

Moreover, these results need scaling analysis and understanding of possible differences in the heat transfer data caused by the differences in geometry and methods for simulation of decay heat. An attempt of such an analysis was presented recently[41], where possible influence of geometry was analyzed.

In order to provide a complete analysis of a full-scale reactor accident, it is necessary to develop models and codes that combine the results from all of the above programs, in addition to those from the Rasplav large-scale tests. Nevertheless, the Rasplav program has provided the following important information:

- corium pool convection was found to be closely simulated by experiments with molten salt mixtures of corresponding Ra' number. This conclusion is confirmed by satisfactory code predictions for the results of full-scale corium and molten-salts tests. Hence, the heat transfer correlations derived from tests with simulant materials can be used to analyze corium pool convection at equivalent Ra' numbers;

- the model developed for interpretation of the non-eutectic salt tests can also be used to describe heat transfer within the transition zone. The model predicts that the solidification front becomes planar under steady-state conditions[46]. Hence, convection within the melt pool should not be affected by formation of a transition zone;

- the large-scale corium experiments demonstrated the possibility of melt stratification inside the corium, which would affect convective circulation in the pool and change the thermal loading on the vessel wall. It is not at all certain, however, that such melt stratification would occur under prototypical conditions, because the data are not yet sufficient to fully understand the influence of variations in corium composition, including the presence of additional chemical components in the corium such as fission products, structural metal oxides and carbon;

- the presently available data indicate that liquid immiscibility will only occur in melts of relatively low oxygen content or with some iron content. Nevertheless, if phase separation and melt stratification were to occur, it is possible that a lower-density metallic rich layer could form on top of the oxygen-rich melt pool;

- some understanding has been gained of the individual behavior of corium melt components (metals, oxides and fission products) at high temperatures. The partitioning of fission products between solid and liquid phases would affect the distribution of decay heat within the lower head, and is, therefore, a contributory factor in the overall heat distribution. The partitioning between metallic and oxidic phases has implications on the heat flux distribution. On the other hand, it has been suggested that fission-product partitioning between solid and liquid phases may not be important for in-vessel retention because the solid fraction of the melt pool will be relatively low. Nevertheless, the knowledge of fission product partitioning may turn out to be necessary for modeling transient situations, such as in-vessel melt progression or ex-vessel corium behavior.

- the Rasplav thermophysical property measurements have made an important contribution to the data required for modeling in-vessel melt behavior.

Despite the advances made within the Rasplav project, there are still many areas of uncertainty in understanding the behavior of molten corium. During the general discussion at the OECD/CSNI Workshop on In-Vessel Core Debris Retention and Coolability, it was concluded that in-vessel corium retention should be quite feasible with large safety margins for medium-power reactors (~600 MW_{el}). This conclusion was based on the results from the plant-specific studies. Nevertheless, the need for further research to address the uncertainties in the convective corium pool behavior was also expressed. In this context, the following aspects were discussed:

- Uncertainties associated with pool formation and with the initial conditions in the lower plenum, both of which will depend on the dimensions and masses of the reactor core components, and on the accident sequence. The current analysis codes use simplified criteria to describe core slumping during the early stages of a severe accident. Hence, there is a need to develop other assessment methods and implement them in the more flexible codes that can be adapted to plant-specific scenarios.

- The thermochemical data bases are still incomplete and need validation (such as miscibility gap in U-Zr-O-Fe, dissolution of oxides and mixtures of molten metals).

- Other uncertainties concern the kinetics of the chemical reactions and the behavior of the different phases (e.g. wetting, density stratification, crust formation). These phenomena depend on different parameters (porosity of the debris, heating rate, the presence of minor compounds such as carbon, boron carbide, boron oxides) and their effects should be investigated.

- Inadequate data of the behavior of the corium components (rates of volatilization, fission product partitioning between layers and phases, decay heat distribution).

Some of the issues were already discussed in detail in the AP600 study report[15] and later in the review report as discussed in a recent paper[42]. The concerns were raised on the mass of metallic material in the core debris, on uranium partitioning between oxide and metal phases for hypostoichiometric reactor fuel, which will determine the degree of stratification into metallic and oxide-rich layers and on exothermic reactions between unoxidized zirconium and steel.

Although recent analysis performed by the French GAREC group[52] indicated that some concerns (such as vaporization, exothermic character of intermetallic reactions) cannot influence strongly the in-vessel retention concept, more analysis is needed to look into these aspects of the problem. E.g. the enhancement of upward heat flux caused by vaporization is very questionable, since (a)

BALI results already showed that the upward heat flux decreased (not increased) when gas was injected through the hemicylindrical surface and (b) boiling of steel is only a transient and not a steady-state situation. On the other hand, the results of the Tulpan T6 test seem to remove the concern that the heat of mixing of Zr rich corium with steel and ablation of steel could be exothermic.

The formation and behavior of the molten pool on the lower support plate depends on the geometry and boundary conditions. Sufficiently detailed analysis on the plant-specific basis is needed in order to define melting and relocation of the fuel and in-core structures, which are needed as input for the molten pool considerations on the lower head.

6. Recommendations

Based on the above discussion on the applicability of the Rasplav results to severe accident modeling, it is recommended that two main areas of further work be pursued. These are: (i) completion of the Rasplav Project and related experiments to solve physicochemical aspects of convective corium pool behavior; and (ii) continued refinement of the models and codes as the results of future experimental work become available. The important issues to be resolved within each area are described below.

6.1. Issues to be resolved by further experiments

The Rasplav Project demonstrated that the U-Zr-O corium melt behaved comparably to the simulant material in its natural circulation, therefore previous evaluations based on simulant material data could be scaled to prototypic reactor conditions. However, two of the four Rasplav tests exhibited an unexpected behavior. Post-test examinations showed that the melt pool, initially of a homogenous composition and density, stratified into two layers of unequal density. Investigations pointed out that the 0.3wt.% carbon contained in the corium composition was responsible for the stratification observed rather than thermodynamic stratification due to the existence of a fairly wide miscibility gap in the phase diagram for the U-Zr-O system. The same investigation led to the consideration that the chemical composition of the corium mixture might change the thermal-hydraulic behavior of the corium pool. These effects can be caused by the presence of materials other than the molten UO_2, ZrO_2, Zr as would be the case for power reactors, where also control rod materials such as boron carbide and burnable poisons can be among the basic constituents of the LWR corium.

Although the miscibility gap boundaries are not accurately known, it would be important to establish whether prototypic corium compositions are likely to fall within the miscibility gap. This would involve examination of hypothetical melt relocation scenarios, such as recently discussed in a CSNI Status Report[35]. The task is very challenging because of the large variety of reactor types and accident progression scenarios, and it is virtually impossible to quantify the melt masses and compositions. It is much more profitable to adopt the bounding approach for estimation of these parameters for a generic investigation.

The stratification caused by relatively small quantities of materials other than UO_2 is likely to affect the thermal loading of the vessel lower head wall. In fact, this effect has already been accounted for the stratified pool system of a metal layer on the top of an oxidic heat generating pool[10, 15]. Stratified pools were observed in large-scale Rasplav tests. Simulant tests conducted at RIT[49a,b] for the latter condition have indicated that stratification can alter, by a factor of 3, the downward heat flux to the vessel.

In a convective uniform oxidic corium pool, it is expected that the fission products will be uniformly distributed, whereas in a corium pool containing metallic components, e.g. Zr and stainless steel, there is a possibility of non-homogeneous distribution of metallic and oxidic fission products. The metallic fission products can attach to the metallic components in the pool and separate into that layer. Consequently, a substantial fraction of the total heat generated could be in the metallic layer, which would reduce the downward heat flux appreciably.

Sufficient knowledge of fission product spatial distribution and of the stratification due to the chemistry of the constituents in the melt pool is lacking. Well-designed experiments obtained with corium compositions prototypical of power reactors would provide the technical support for assessments of the in-vessel melt pool retention strategy as well as of ex-vessel melt management schemes. The MASCA tests are intended to cover this accident management need.

The molten-salt test facility could also be used for experiments with a stratified molten pool containing a thin metallic layer. These experiments, together with the SIMECO experiments at the RIT, and the experiments at the COPO II facility in Finland would allow the quantification of the ”focusing” effect (i.e., the local increase in heat flux caused by the presence of a thin metal layer). Separation and stratification of the corium could also be added to the experimental simulation, after establishing their technical feasibility. Such experiments will complement the MASCA program and provide data for the validation of the computer codes modeling the integral behavior of the in-vessel retention strategy.

Finally, the physical property measurements should be continued, and their relevance to severe accident phenomena established. For successful modeling of reactor accidents, the following material properties should be known for corium as a function of chemical composition: heat capacity, thermal conductivity, viscosity, density, emissivity, and surface tension. The critical properties governing prolonged in-vessel retention of molten corium are probably the density and thermal conductivity. The densities of different corium compositions may significantly influence the extent of stratification, and thus, the vessel thermal loading. The thermal conductivity of corium is likely to depend significantly on the unoxidized zirconium content. The corium surface tension could play a role in corium relocation behavior, and the likelihood of steam explosions.

6.2. Long term code development

As mentioned above, additional code development work is still needed to address the full range of likely accident scenarios. The objectives of this work is twofold: (1) the applicability of computational fluid dynamics (CFD) codes should be extended to the reactor conditions; and (2) analysis methods should be further developed to simulate late phase core degradation and the transient heatup process on the lower head.

The code development recommended for verifying the in-vessel retention concept can be divided into four main activities:

1. melt pool thermal hydraulics,
2. corium chemical behavior and interactions,
3. mechanical response of the reactor vessel; and
4. upper crust stability.

To simulate corium convection, the applicability range of the codes needs to be extended from the current Rayleigh number limit of $\leq 10^{14}$ up to values of 10^{16} - 10^{17}. In turn, this will require development and assessment of a turbulence model. At present, there is no generally accepted turbulence model for predicting heat transfer from the molten corium pool to the wall. Turbulence at the upper interface of the molten pool is mainly due to Rayleigh-Bénard instabilities. These instabilities have been studied experimentally in detail in a volumetrically heated pool[50]. The link between the physics of these instabilities and the heat transfer correlations were also studied and the results[50] should be considered for code development.

Corium thermochemical models cannot be developed further, before the controlling phenomena in the Rasplav experiments have been identified. As a first step, the existing codes (based on thermal convection, and validated for Rayleigh numbers of $\leq 10^{14}$) could be used to simulate heat transfer in a melt pool with an assumed level of stratification, comparing the code predictions with the test results. Nevertheless, it may turn out to be necessary to incorporate additional models for chemical diffusion and thermal diffusion into the existing codes, together with an extended data base for materials properties. The ultimate goal for code development can be set as to predict correctly corium thermochemical behavior, such as crust formation, uranium and fission-product partitioning between the different layers and phases, and intermetallic exothermic reactions between zirconium and steel. However, the relevance of modeling is not necessarily increasing with the degree of the complexity. As far as corium is concerned, it will be very difficult to determine experimentally the needed parameters with enough accuracy.

As discussed during the OECD/CSNI Workshop on In-Vessel Retention and Coolability in March 1998, it is important to understand the mechanical behavior and failure mode of the RPV lower head, i.e. failure time and location as well as the hole size, and to improve the modeling of vessel creep rupture. Problems are anticipated in simulating the vessel wall penetration and the behavior of welded regions. The effect of stress redistribution for high prototypical temperature gradients through the vessel wall is not well understood. The effect of stress redistribution is currently being examined in the OECD Lower Head Failure program at the Sandia National Laboratories.

Realistic melt relocation predictions for the late-phase core degradation process would be useful in decreasing uncertainties and in defining conditions within the lower plenum. The predictions should account for the internal vessel structures and hence, they should be very plant-specific. If any code was developed for that purpose, it should include models for in-core melt formation and growth; melting and refreezing of initially formed blockages; melting of in-vessel structures; behavior and relocation of corium, structure material melt or debris; and subsequent pool or debris-bed formation, including structure ablation. The code should also include corium chemistry models as it was discussed above. The development of such an all-inclusive code is obviously a very difficult, if not impossible task, considering the large gaps in the current data base and the complex nature of the problem. Without such a code, however, it is difficult to predict the corium composition and behavior (relocation, stratification, etc.) accurately to support the in-vessel retention concept. Alternatively, a bounding state can be assumed as it has been done with the ROAAM methodology successfully to both the AP600[15] and Loviisa[2] in-vessel retention studies.

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