

CEA APPROACH TO THE MODELLING OF CORIUM BEHAVIOUR AND THE PLACE OF MASCA

J.M. Seiler, K. Froment, B. Tourniaire
CEA Grenoble - DEN/DTN/SE2T/LPTM

Abstract

CEA has undertaken an original approach to the modelling of corium behaviour for In-Vessel and Ex-Vessel situations. This approach is based on a strong coupling between physicochemistry and thermalhydraulics. The aim is to derive (in a physically consistent way) deterministic interface conditions, stratification criteria and physical properties to be used for the calculation of heat flux distributions, melt temperatures and material interactions.

The approach has been first developed for oxidic corium pool. It has been shown that no mushy zone can exist in thermalhydraulic steady state in the absence of mass transfer. The interface temperature is then equal to the liquidus temperature corresponding to the actual melt composition (that may evolve versus time). The melt is then completely liquid and the viscosity is low. The dissolution of ceramics is described with the same approach. This applies directly to In-Vessel corium pools and corium retention in core-catchers. The approach has been validated against a number of real material experiments (RASPLAV, CIT, VULCANO) and simulant material experiments (RASPLAV Salt, SIMECO). The problem of molten corium/concrete interaction (MCCI) is more complex since it involves mass transfer due to the melting of concrete and to gas sparging. It has been shown, through comparison to many experiments, that the approach provides a good description of the evolution of melt temperature (that, again, follows the liquidus temperature) and provides rational explanations for material effects on melt temperature and for the occurrence of ablation instabilities. A methodology has been derived for the calculation of melt viscosities and validated. This approach permitted, for the first time, to define similarity criteria. Following this analysis, analytical experiments with simulant material (ARTEMIS) have been engaged for a better understanding of the melt behaviour at the interface with concrete. The same approach has been applied to oxide-metal melts (including molten steel). It has rapidly revealed that the behaviour of such mixtures depends on whether or not they come to physicochemical equilibrium. If they come to physicochemical equilibrium, and depending on the level of oxidation of zirconium, inverse stratification can occur. The model describing the behaviour of such melts has been derived by CEA in a way consistent with the preceding models. The model has been validated against MASCA tests (prediction of compositions, densities and interface conditions) and SIMECO experiments (transient dissolution of top layer, heat flux distribution). Consequences on In-Vessel Retention and on interaction with ceramics (core-catchers) have been outlined.

Introduction

The aim of the R&D studies undertaken at CEA is to improve the understanding of the physical behaviour of corium in severe accidents. The lack of understanding of this behaviour leads to many difficulties:

- Arbitrary hypotheses on space distribution of corium (layering, mixing,...)
- Arbitrary hypotheses on boundary conditions (interface temperature, mushy zones, ...) which have a strong impact on heat flux distributions,
- Non coherency of hypotheses taken for the description of different situations in severe accident,
- Difficulties to apprehend experimental system effects due to test procedures, materials effect, and thus, their consequences on extrapolations at reactor scale,
- Permanent doubts on the representativity of results obtained with simulant materials including high temperature materials (effect of mushy zones, representativity of alumina melts,...)

An understanding of corium behaviour is the key to answering these questions.

Since the behaviour is basically linked to the physicochemical properties, a tool to characterize quantitatively this behaviour is obviously the thermodynamic approach.

Prediction of corium composition and density stratifications. Limits of thermodynamic calculations

As mentioned previously, corium behaviour is basically linked to the physicochemical properties of corium pool. These properties have to be determined in terms of the number of phases (miscible or immiscible), phase compositions, solidus and liquidus temperature and variation of solid fraction as a function of temperature.

In this view, since 1989, THERMODATA/INPG/CNRS with the sponsorship of IRSN has been developing, within the CALPHAD approach, a thermodynamical database for the corium (NUCLEA04). This database, which represents at this time a 18 element system Ag-Al-B-Ba-C-Ca-Cr-Fe-In-La-Mg-Ni-O-Ru-Si-Sr-U-Zr for the condensed phases, includes the main interacting materials, i.e. fuel (UO_2), zircaloy (Zr), steel structures (Cr, Fe, Ni), control rods (Ag, B, C, In), fission products (Ba, La, Ru, Sr) and concrete (Al_2O_3 , CaO, FeO, Al_2O_3 , MgO, SiO_2). The modelling and critical assessment of all the binary and the most important higher-order sub-systems (metallic, oxide and metal-oxide/oxygen) have been recently reviewed in the framework of the ENTHALPY Programme.

Since 1994, CEA has been developing within the same methodology, a 4 elements U-Zr-Fe-O thermodynamical database (called DPC01) for nuclear applications.

Thermodynamic calculations (which suppose uniform temperature and constant composition) cannot be directly applied for reactor applications since reactor situations involve heat and mass transfer, non isothermal and transient situations. Thus the main contribution of CEA approach is in establishing a link between the physicochemical behaviour predicted by thermodynamics and the multiphase heat and mass transfer problems linked to severe accidents.

Thermalhydraulic steady state in Oxidic corium pools

A key step in the quest of the link between physicochemistry and multiphase phenomena is the determination of the interface conditions in thermalhydraulic steady state. In the application to corium pools, thermalhydraulic steady state corresponds to constant (vs. time) heat flux distribution at the boundaries of the different corium volumes. Constant heat flux means constant thickness of solid crust. This is a different definition than the definition of steady state in metallurgy where steady state means constant freezing rate. In thermalhydraulic steady state applied to corium pools, the freezing rate (i.e. the variation of crust thickness vs. time) is equal to zero. This has three main consequences [2]:

- The interface temperature between liquid and crust is equal to the liquidus temperature of the considered liquid layer,
- There is no mushy zone. The interface between the liquid and crust is plane front (in the metallurgical sense) despite the existence of a melting interval (even large). For heat transfer, the interface temperature is the liquidus temperature of the residual liquid (or actual liquid). In corium mixtures, this liquidus temperature can be up to 1000 K higher than the solidus temperature.
- When a single phase is surrounded by a crust, the composition of the liquid at the interface is equal to the composition of the bulk. The crust at the interface contains the most refractory materials (generally UO_2 and ZrO_2). The pool consists in a liquid surrounded by a refractory crust (no solid particle in suspension in the liquid).

A consequence is that effects of mushy zone have not to be taken into account for the calculation of heat transfer in steady state. The heat transfer correlations derived from simulant material experiments (using pure materials such as water and constant temperature boundary conditions) can thus be extrapolated to corium pools in steady state. Another consequence is that the viscosity of the liquid corium is small since, due to heat transfer in the pool, the temperature in the liquid is everywhere in the pool above liquidus temperature.

It is also shown that test procedures have strong impact on final (steady state) temperature, but have much weaker influence on final heat flux distribution, when non-eutectic materials are used [2]. This implies that not only the choice of simulant materials, but also test procedures should be carefully examined, in simulant and in real materials: the composition of the crust that may form around a corium pool is different whether it results from the solidification of the pool with a slow transient (enrichment in refractory species) or whether it results from an incomplete melting of the initial material (same composition as the bulk). This has been confirmed in the frame of the RASPLAV-Salt experiments ; the temperature in the steady state situation depends on the test procedure when non-eutectic melts are used. Simulation criteria have been proposed; nevertheless, their use requires a deep understanding of the phenomenology and is not straightforward.

In the reactor situation, the decay of the residual power is very slow. The decrease of melt temperature and the increase of crust thickness can be described with the assumption of successive steady state situations. The refractory materials deposit in the crust in the long time transient and the liquid is depleted in refractory materials. Thus, the composition of the liquid changes vs. time. A consequence is that the liquidus, and thus the interface temperature, changes. This leads to the concept of “living” (i.e. evolutive) interface temperature.

Thermalhydraulic steady state for Oxidic and Metallic corium pools

The classical picture of bounding conditions for in-vessel retention considers a molten metallic layer (steel + zirconium) located above the oxidic corium. The metal layer is separated from the oxidic pool by a thin solid crust. Both layers are supposed to not come to physicochemical equilibrium. In that case the interface condition between the oxidic pool and its crust is the liquidus temperature (corresponding to the oxidic pool composition) and the interface condition between the metal layer and the vessel is the liquidus temperature of the metal phase (that is near to the melting temperature of the steel).

In MASCA, it has been demonstrated that oxidic and metallic liquid layers can reach physicochemical equilibrium, which leads to a different layer configuration in which a part of the metal may relocate below the oxidic pool. Although this conclusion has been previously outlined by several authors [2-8, 27], several features of this configuration had not been clearly addressed and MASCA helps to highlight these features.

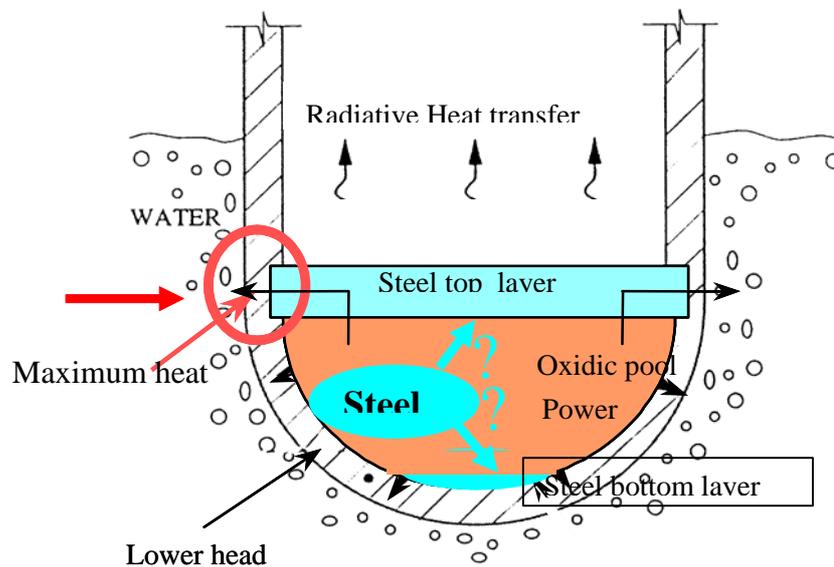


Figure 1: The inverse stratification of metal layer. The bottom metal layer comes to thermodynamic equilibrium with the oxidic pool. Both oxidic and bottom metal layers are surrounded, on the interface, by the same oxidic material

From the thermodynamic point of view, this situation is characteristic of system with miscibility gap (cf. Figure 2). This means that two immiscible oxidic and metallic layers may exist in physicochemical equilibrium, but with slight reciprocal dissolution. The metal becomes denser than the oxide because it dissolves uranium. The amount of free zirconium and the amount of steel control both the reciprocal dissolution and the densities of the layers [9].

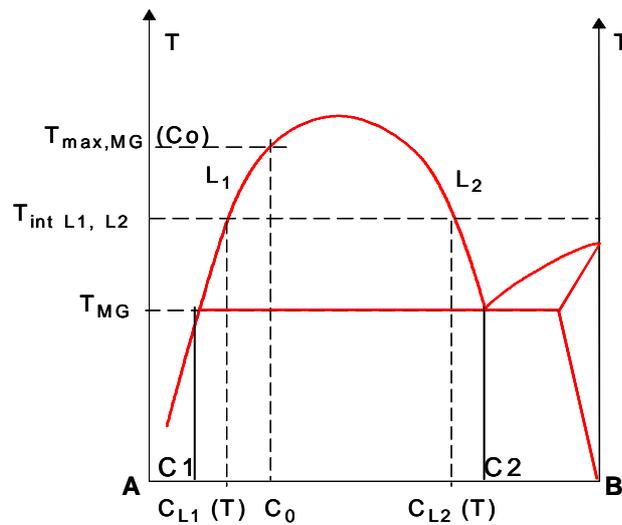


Figure 2 : Corium pool with miscibility gap

The reciprocal statement is also true: if the metal layer becomes denser, it means that uranium is dissolved in it. If uranium is dissolved, some physicochemical equilibrium has consequently been reached with the oxidic phase. Both liquids (oxidic and metallic) are in contact with an oxidic crust and the composition of the oxidic material on the interface with the solid is the same (oxidic refractory material). The interface temperature between both layers and the crust is the same and is T_{MG} , the transition temperature into the miscibility gap (which corresponds to the liquidus temperature). Both liquids are in direct contact (no solid layer at the interface between both liquids layers) and the interface temperature between the liquid layers is higher than T_{MG} . One of the consequences is that the metal layer cannot be in direct contact with the vessel steel.

A model has been developed [10,11] that allows to determine i) the composition of the layers, ii) their densities, iii) the thickness of the layers, iv) the interface temperature between both layers and v) the heat distribution at the boundaries. This model has been validated against available data from SIMECO [12-13] and from MASCA. Characteristic time delays that are necessary to reach thermodynamic equilibrium conditions have been derived. The model predicts a secondary effect: the existence of globules of liquids in the boundary layers of both phases. Such globules have been observed in MASCA [14] and in ISABEL tests [3].

A reactor application has been performed [11]. It has been shown that the time delay necessary for reaching thermodynamic equilibrium is comparable with the time delay necessary for reaching thermalhydraulic steady state conditions. In the reactor application the amount of metal that may reach physicochemical equilibrium with the oxidic phase depends strongly on the transient corium relocation and remelting events in the lower head. Bounding assumptions have been considered for a three layer configuration: a bottom metal layer that comes to thermodynamic equilibrium with the oxidic pool and a top molten steel layer. The main consequence is a significant increase of the total mass of steel that is necessary to keep the heat flux below CHF [11].

MASCA is a key link for the extrapolation of the modelling developed for the behaviour of oxidic corium pools to the modelling of oxidic + metallic pools, and, from that, to the extrapolation to corium-ceramic interaction.

Thermalhydraulic steady state in a core catcher involving a contact between corium and ceramic

Oxidic corium

Concepts of core-catchers generally involve ceramic protection layers which are considered as refractory compounds. For thick ceramic layers the interface temperature in thermalhydraulic steady state between corium and ceramic can reach the liquidus temperature of the oxidic corium. In that case [15, 16] the interface temperature between the oxidic corium and the surrounding material is the liquidus temperature of the oxidic liquid, independently of the nature of this solid material: a crust of corium or an oxidic ceramic material. In other words the oxidic ceramic behaves like oxidic crust material from the corium. In that case the ceramic will be dissolved into the molten oxidic corium.

A model describing the steady state situation of a ceramic crucible containing volumetrically heated oxidic corium has been developed [16]. This model has been validated against CIT tests [16] performed in NITI Saint Petersburg.

An important consequence of this approach is that there is no necessity of making use of expensive thick refractory ceramic layers to protect a core catcher. A standard sacrificial concrete, designed to withstand the thermal shock at the arrival of corium, should be sufficient. If the thickness of the layer is not sufficient, the corium will imbed itself in its proper crust.

Oxidic and Metallic layers

The case of interest that is considered here is the case where a metallic layer is placed between the ceramic and the oxidic corium in order to protect the ceramic from dissolution by oxidic corium. It is also assumed here that the ceramic is sufficiently thick to allow for elevated temperature in the oxidic layer: in other words, there is no crust between the oxidic corium and the metal layer and the liquid metal is in direct contact with the liquid oxides. In that case the temperature in the metal layer is very near to the temperature of oxidic liquid, due to the high thermal conductivity of the metal. Under such conditions, both metal and oxidic layers come to physicochemical equilibrium. The time delay that is needed for reaching physicochemical equilibrium would be much less than the delay of decrease of the residual power. When physicochemical equilibrium conditions are reached between oxidic and metallic layers, the metallic phase will be able to dissolve the ceramic. A model has been developed to predict the final steady state situation and the ablation of the ceramic in such a layered configuration. MASCA MA1 test is also claimed to be representative of such a situation: the oxidic and the metallic corium, which come to physicochemical equilibrium, may ablate the surrounding refractory material (UO₂) whose residual thickness is controlled by the heat flux distribution, conduction heat transfer in the residual solid and external cooling.

The conclusion for the reactor application is that there is no great interest for putting a metal layer between the oxidic corium and the ceramic. In the long term, the metal layer that is in physicochemical equilibrium with the liquid oxide will be able to dissolve a thick ceramic layer. The final residual thickness of the ceramic will not be different from the situation where the oxidic corium is in direct contact with the ceramic material. The main difference is that the presence of the metal layer introduces a delay to the dissolution of the ceramic.

Molten Corium Concrete Interaction (MCCI)

Corium concrete interaction is a much more complex situation than the previous ones. The additional complexity comes from the continuous introduction of molten concrete into the corium and from the two phase effects linked to gas sparging.

By evidence the temperature difference between the liquidus temperature of the oxidic corium and the melting temperature of concrete is very high (between 500 and 1000 K). Below liquidus temperature, the oxidic corium begins to precipitate solid refractory material (^{NB1}). Ablation liquid material from the concrete cannot dissolve these refractory precipitates at the melting temperature of concrete. Thus it is straightforward to suppose that refractory materials (UO₂ and ZrO₂) will concentrate near to the interface between corium and concrete. However, the hydrodynamic effects linked to the continuous introduction of molten concrete in the melt and the stirring by sparging gases will have a counteracting effect. For the time being, there is no deterministic approach available for describing these counteracting effects.

Considering the large temperature interval between liquidus and the melting of concrete, CEA has developed a simplified MCCI model approach [2,17,20] based on the hypothesis that a refractory crust is able to form at the interface between oxidic corium and concrete. Post mortem examinations of ACE and MACE residues have also shown some accumulation of refractory species at the interface [18-19]. In this frame, the interface temperature between corium and the crust tends then towards the liquidus temperature of the oxidic melt and the viscosity of the oxidic melt remains low. Thus, the temperature difference between the bulk and the interface with the crust is small which means that the temperature in the melt is near to the liquidus temperature. This has been verified recently on the MCCI test performed at Framatome Erlangen in the frame of the ECOSTAR project. From these tests it could also be concluded that the temperature gradient is located in a very thin layer at the interface. During the ablation, oxidic material from the concrete decomposition is mixed with the corium. Thus, the concentration of non-refractory oxides increases vs. time and the associated liquidus temperature decreases. This quantitatively explains the decrease of temperature vs. time in the ACE and MACE experiments. The same effect explains the observed decrease of the melt temperature when iron oxide is initially added to the corium material (ACE L5).

The model also provides an explanation of the stepwise and periodic erosion of concrete that is observed in the experiments. This is explained by a crust instability linked to periodic accumulation of molten concrete below a refractory crust. The order of magnitude of the period could be obtained quantitatively.

The higher content in non-refractory species of the material that has been ejected in the experiment and the fact that the pool temperature remains constant after an increase by a factor two of the power supply in the MACE M3B could also be quantitatively explained with this model approach

One of the main outcomes for the reactor application is that the initial conditions for corium spreading, for instance on the EPR core-catcher, are better known. As the temperature in the liquid oxides is near to liquidus, the viscosity of the molten oxides is small.

However several effects are still unexplained; for instance, despite the fact that the temperature in the melt was near to liquidus and that the temperature gradient was located in a thin layer in the recent MCCI test performed by Framatome Erlangen, no well identified solid crust could be evidenced. MCCI modelling needs complementary work. Furthermore, no MCCI experiments with oxidic and metallic corium are available in real materials. Therefore CEA has undertaken dedicated experiments with simulant materials (ARTEMIS) and real materials (VULCANO).

Summary of interface conditions

Table 1 presents a summary of the best estimate interface conditions between melt and solid that have been derived from the CEA approach. On this table, the main experimental programmes that helped to validate the approach are mentioned. Of course, several experiments performed with simulant materials have also strongly contributed to validate the approach but are not mentioned on the table.

		Oxidic corium	Metallic corium	
			Metal in thermodynamic equilibrium with molten oxides	Metal out of thermodynamic equilibrium with liquid oxides
In-vessel pool	RASPLAV VULCAN	T liquidus	→ T liquidus = T_{MG}	Own T liquidus for each layer
	MASCA		↓	
Corium- ceramic interaction	CIT	T liquidus	T liquidus = T_{MG}	Own T liquidus for each layer
			↓	
Corium concrete interaction	ACE & MACE	↓ T liquidus	↓	?
		T liquidus	?	

Table 1: Summary of best estimate interface conditions (between melt and solid layer) for three reactor situation involving molten corium layers. The place of real materials tests.

The viscosity of oxidic corium

CEA has also developed a quantitative predictive model for the viscosity of oxidic corium [2,21]. Thermodynamic calculations are used to determine, for a given composition and a given temperature, the solid fraction and the composition of the residual liquid. The residual liquid is considered as the carrying phase. The viscosity of this liquid is determined with a methodology that has been developed for the prediction of the viscosity of lava flows [24]. The effect of the solid phase on the apparent viscosity is taken into account by adding a correction factor. This correction factor depends on the solid volumetric fraction but also on the shape of the solid particles. Several correlations have been proposed for the effect of the solid fraction. The shape of the solid particles depends on several parameters such as the shear rate and the cooling rate. Non-newtonian effects are related to the behaviour of the solid phase. Recently a methodology has been developed [22] for the prediction of the effect of shear stress on particles shape and apparent viscosity. This methodology has been successfully applied to the recalculation of the viscosity measurement performed at ANL [23] and BATTELLE [2,21]. Further improvements for the effects of solid fraction have been proposed [25]. The methodology is used for the prediction of the viscosity of melts undergoing rapid cooling, like

during spreading [26]. The methodology is also used for the prediction of the viscosity of the oxidic corium above liquidus temperature and application to In-Vessel corium pools, corium-ceramic interaction and corium-concrete interaction.

NB1: this is not the case with alumina melts. For alumina melts the liquidus temperature can decrease below the melting temperature of iron.

Conclusion

The approach developed by CEA has the objective to provide a consistent physical description of the behaviour of corium in various reactor situations. One of the significant outcome is the interface temperature between molten material and the surrounding solid in thermalhydraulic steady state. This temperature is equal to the liquidus temperature when the surrounding material is a crust (that is issued from the corium itself) or a material that can be dissolved into the considered corium layer (for instance ceramic material in contact with oxidic corium or molten metal layer in contact with solid steel). When the liquid metal comes to physico-chemical equilibrium with the liquid oxides, this interface condition holds simultaneously for both layers (application to inverse metal stratification in the lower head and to corium – ceramic interaction). This interface temperature revealed also to be the best estimate interface temperature for MCCI (molten corium-concrete interaction). When the composition of the corium varies vs. time, the liquidus temperature varies, which leads to the concept of “living” interface temperature. In the case of MCCI the phenomenology is however much more complex and the validity limits of this interface condition are not well known (further R&D needed).

The outcome of the methodology concerning the interface temperature between liquid corium and the surrounding solid should not be separated from the other consequences of the approach. Compositions of liquid and solid phases, physical properties like viscosity, and even the mass (of metal and oxide) contained in each layer are closely and consistently connected to the interface temperature. The approach requires that physicochemistry and thermalhydraulics are placed at the same importance level for the understanding of multiphase phenomena in severe accidents of LWRs.

In this approach, MASCA is a key link for the extrapolation of the modelling developed for the behaviour of oxidic corium pools to the modelling of oxidic + metallic pools, and, starting from that, to the extrapolation to more complex reactor situations (like corium-ceramic interaction).

References

- [1] NUCLEA04 Database, INPG/CNRS/THERMODATA, Test version (2004)
- [2] Seiler J.M., Froment K., 2000 “Material effects on multiphase phenomena in late phases of severe accidents of nuclear reactors” Multiphase Science and Technology, Vol. 12, N° 2, pp 117-257
- [3] Gueneau C., Dauvois V., Perodeaud P., Gonella C., Dugne O., 1998 "Liquid immiscibility in a (U,O,Zr) model corium" Journal of Nuclear Materials, n°254, pp 158-174
- [4] Hofmann P., 1976 „Reactions- und Schmelzverhalten der LWR-Corekomponenten UO₂, Zircaloy and Stahl während des Abschmelzperiode“ FKF 2220, Juli 1976
- [5] Kim K.T., Olander D.R., 1988 “Dissolution of Uranium Dioxide by Molten Zircaloy“ Journal of Nuclear materials, 154, 1988, pp 85-101

- [6] Parker G.W., Hodge S.A., 1990 "Small scale BWR Core Debris Eutectics Formation and Melting Experiment" Nuclear engineering and Design, 121, 1990, pp 341-347
- [7] Rempe J.L., Knudson D.L., Allison C.M., Thinnis G.L., Atwood C.L., Cebull M.J., 1997, "Potential for AP600 In-Vessel Retention through Ex-Vessel Flooding" INEEL/EXT-97-00779
- [8] Powers D.A., Chemical Phenomena and FP Behavior during Core Debris/Concrete Interactions, Proc. CSNI Specialist Meeting on Core Debris Concrete Interaction EPRI NP-5054-SR february, (1987)
- [9] Barrachin M., Defoort F., 2004 "Thermophysical properties of In-Vessel corium: MASCA programme related results" MASCA seminar June 10-11 Aix-En-Provence France
- [10] Seiler J.M., Fouquet A., Froment K. and Defoort F. 2003, "Theoretical Analysis for Corium Pool with Miscibility Gap", Nuclear Technology, Vol. 141, 233 (2003)
- [11] Seiler J.M., Froment K. Defoort F., Fichot F., 2004 "The thermalhydraulics of corium pools undergoing a miscibility gap, model development and reactor applications" MASCA Seminar June 10-11 Aix En province France
- [12] Theerthan S.A., Kolb G., Sehgal B.R. , 2000-1 "The role of phase separation on heat transfer in internally heated liquid layers" Proc. ICONE 8th International Conference on Nuclear Engineering April 2-6, 2000, Baltimore USA
- [13] Theerthan S.A., Kolb G., Sehgal B.R., 2000 "Heat transfer in internally heated liquid layers with stable stratification induced by phase separation" Proc. of Nat. Heat Transfer Conf., Pittsburg, PA, USA, 20-22 August 2000
- [14] Bechta S., 2001 "Zr partitioning tests in the cold crucible test MA-1" OECD MASCA meeting, April 17-19, Helsinki
- [15] Seiler J.M., Labergri F., Froment K., Valin F. "Model development for the calculation of corium-ceramic interaction during severe accidents in LWRs" 9th Int. Topical Meeting on Nuclear Reactor Thermal Hydraulics NURETH 9 San Francisco, California, Oct 3-8 1999
- [16] Froment K., Duret B., Seiler J.M., 1999 "Analysis of ceramic ablation by oxidic corium" OECD Workshop on Ex-Vessel debris coolability, Karlsruhe, Germany, November 15-18, 1999
- [17] Seiler J.M. "Phase segregation model applied to Molten Pool thermalhydraulics during MCCI" ASME/AIChE/ANS National Heat transfer Conference. Portland 3-5 August 1995
- [18] Farmer M.T., Aeschlimann R.W., Kilsdonk D.J., 1998-1, "Results of M3B posttest examinations" MACE TAC Meeting, ANL
- [19] Farmer M.T., Kilsdonk D.J., Kras A.J., 1998-2, "Results of corium composition gradient measurements for ACE/MCCI tests L2 and L5" ACEX-TR-C24, May 1998
- [20] Seiler J.M. "Phase segregation model and molten pool thermalhydraulics during molten corium concrete interaction" Nuclear Engineering and design 166 [1996] 259-267.
- [21] Seiler J.M., Ganzhorn J. "Viscosities of corium-concrete mixtures" Nuclear Engineering and Design Vol 178 (1997) N°3 December IV pp 413-427
- [22] Perez M., Barbe J.C., Neda Z., Brechet Y., Salvo L."Computer simulation of the microstructure and rheology of semi-solid alloys under shear" Acta Materialia 48, 3773-3782
- [23] Roche M.F., Steidl P.F., Leibowitz L., Fink J.K. and Sehgal B.R., 1993 "Viscosity of Corium Concrete Mixtures at High Temperatures", ACE-TR-C37

- [24] Urbain G., 1981 "Viscosity of silicate melts", *Trans. J. Br. Ceram. Soc.*, 80, 139-141
- [25] Ramacciotti M., Journeau C., Sudreau F. « Viscosity models for corium melts » *Nuclear Engineering and Design* , 2001, N°204, pp 377-389
- [26] Spindler B., Veteau J.M., Brayer C. "Assessment of THEMA code against spreading experiments" OECD Workshop on Ex-Vessel debris coolability, Karlsruhe, Germany, 15-18 November 1999
- [27] Hayward P.J., George I.M., "Dissolution of UO₂ in molten zircalloy 4" *Journal of Nuclear materials*, 232, 1996