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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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OECD WORKSHOP ON EX-VESSEL DEBRIS COOLABILITY

SUMMARY AND RECOMMENDATIONS

Held in Karlsruhe, Germany, on 15-18 November 1999

English text only

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996) and the Republic of Korea (12th December 1996). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of 27 OECD Member countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its Member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

CSNI

The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of senior scientists and engineers, with broad responsibilities for safety technology and research programmes, and representatives from regulatory authorities. It was set up in 1973 to develop and co-ordinate the activities of the NEA concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations. The Committee's purpose is to foster international co-operation in nuclear safety amongst the OECD Member countries. CSNI's main tasks are to exchange technical information and to promote collaboration between research, development, engineering and regulation organisations; to review the state of knowledge on selected topics of nuclear safety technology and safety assessments, including operating experience; to initiate and conduct programmes to overcome discrepancies, develop improvements and reach consensus on technical issues; to promote co-ordination of work, including the establishment of joint undertakings.

PWG4

CSNI's Principal Working Group on the Confinement of Accidental Radioactive Releases (PWG4) has been given two tasks: containment protection, and fission product retention. Its role is to exchange information on national and international activities in the areas of severe accident phenomena in the containment, fission product phenomena in the primary circuit and the containment, and containment aspects of severe accident management. PWG4 discusses technical issues/reports and their implications, and the results of International Standard Problem (ISP) exercises and specialist meetings, and submits conclusions to the CSNI. It prepares Technical Opinion Papers on major issues. It reviews the main orientations, future trends, emerging issues, co-ordination and interface with other groups in the field of confinement of accidental radioactive releases, identifies necessary activities, and proposes a programme of work to the CSNI.

SAC

The Task Group on Severe Accident Phenomena in the Containment (SAC) is a specialised extension of PWG4. Its main tasks are to exchange information, discuss results and programmes, write state-of-the-art reports, organise specialist workshops, and perform ISP exercises in the field of severe accident phenomenology.

General

An OECD Workshop on Ex-Vessel Debris Coolability was organised in Karlsruhe, Germany, from 15 to 18 November 1999, in collaboration with Forschungszentrum Karlsruhe GmbH. This Summary has been prepared by the Programme Committee of the Workshop and the Session Chairmen (see Annex I).

The meeting was attended by more than eighty specialists representing thirteen OECD Member countries, the European Commission, the Republic of Kazakhstan and the Russian Federation. Forty-eight papers were presented; three additional Russian papers were distributed during the Workshop.

A first OECD Specialist Meeting on Core Debris-Concrete Interactions had been held in Palo Alto, California in September 1986, and a second one in Karlsruhe in April 1992. The OECD Workshop on Large Molten Pool Heat Transfer held in Grenoble, France in March 1994 had recommended holding a workshop on ex-vessel melt coolability by spreading in due course. More recently it had been agreed that it would also be useful to discuss other forms of debris coolability, e.g., coolability by an overlying water pool (MACE experiments), and melt quenching (FARO experiments). Furthermore, a series of relatively new investigations, both theoretical and experimental, was underway in Europe, studying the basic processes to achieve coolability. This work is relevant for existing as well as for future reactors. Japan also had started COTELS experiments focused on ex-vessel corium coolability for existing plants.

Considering the large amount of work done in recent years, the Committee on the Safety of Nuclear Installations (CSNI) concluded that the time was ripe to bring all the new information together, and decided to sponsor a new workshop. The meeting organised in Karlsruhe was complementary to the OECD Workshop on In-Vessel Core Debris Retention and Coolability held in Garching, Germany in March 1998.

The objectives of the Workshop were to:

- exchange information on past, present and planned R&D activities in the area of ex-vessel debris coolability, and promote collaboration among the experts;
- review the present situation and identify areas where knowledge is adequate for plant application;
- address major uncertainties and identify remaining issues relevant to reactor safety;
- discuss future orientations of work;
- propose conclusions and recommendations to the CSNI.

The Workshop had four main sessions, some of them divided into sub-sessions:

Session A: Special Modes of Corium Discharge into the Containment

Session B: Phenomena to Achieve Coolability

B1: Natural Convection Heat Transfer with Bubbling

B2: Characteristics of Particle Beds

B3: Spreading

B4: Fragmentation and Quenching

B5: Flooding

Session C: Material Properties and Thermochemistry

C1: Properties

C2: Thermochemistry

Session D: Reactor Application

The Session Chairmen summaries are attached (Annex II). Each session and the meeting itself were concluded by a general discussion. Throughout the presentations of the papers and the discussions, the focus was on the application to the full size plant.

Summary

The workshop has underlined that international scientific co-operation is an important factor to assure and to increase the safety level of operating and future nuclear power plants in Western Europe, USA, Japan, and Eastern European countries as well. The similarity and convergence of the technical approaches and strategies of severe accident control and mitigation, as presented by specialists of many countries, was noted as a positive response to the requirements of safe reactor operation.

The workshop has shown a substantial increase of research and design activities to control ex-vessel melts. Especially in Western Europe, this increase is related to higher safety requirements in response to technological improvements and a highly sensitive political background. As addressed in the invited introductory paper, besides the strong interest to mitigate severe accident consequences in existing plants, future evolutionary LWRs in Europe (as the European Pressurised Reactor EPR) will include additional design features for mitigation of severe accidents involving vessel melt-through.

The following gives an overview of the current aspects in ex-vessel safety research, in the sequence of the melt-down process:

As the release mode of the corium debris from the pressure vessel is unknown to a substantial degree, bounding scenarios are addressed to quantify different possible aspects of corium release. DISCO investigations study the ejection of melt in narrow reactor cavities in case that the lower pressure vessel head fails under reduced system pressure. The dispersal and location of melt in the cavity and/or the reactor containment are important with respect e.g. to any subsequent cooling measure, and strongly depend on release pressure and location of RPV failure hole. Code development to describe melt relocation is underway.

Jet impingement is another generic question related to corium release. Experiments study the erosion rate of concrete as influenced by the properties of the jet, and will be supplemented by model development.

Possible types of concrete, which are under consideration for use as sacrificial structure material for corium melts are investigated in KAPOOL experiments to quantify their erosion behaviour. Additionally, the erosion of a steel gate is investigated to assure sufficient large opening for the release of the corium melt to a dedicated spreading area.

Heat transfer from the internally heated melt during concrete erosion is investigated with model fluids especially with respect to the onset of solidification. The agitation by gas bubbles provides for a more balanced upward and downward heat transfer. Other experiments show that solid particles suspended in the melt, which simulate a slurry melt after onset of partial solidification, influence the heat transfer mainly because of the higher viscosity of the dispersion.

Several contributions discussed the coupling of thermal-hydraulic and physico-chemical effects during solidification of multi-component corium melts and MCCI. Under low freezing rate, a solid layer of the refractory components of the melt would form at the cold interface, instead of a mushy fluid modelled in actual codes. As this new approach gives better understanding and description of the phenomena observed in MCCI and material interaction experiments, its implementation into codes is desirable for better predictive capability. However, because of the complicated physico-chemical processes and the complex physico-chemical databases, this is a very difficult task.

When a hot corium melt is introduced into a water pool, a particle bed may form. The coolability of such particle beds when flooded by water was analysed and can substantially be improved, when the water is supplied by downcomers to the bottom of the particle bed. Further experimental work is underway to characterise the influence of 3D-effects on bed coolability.

Spreading of corium to generate a shallow melt layer is of interest to generate a good condition for melt cooling. From the experiments performed within the 4th European Commission Framework Programme both with simulant (CORINE, KATS, RIT) and prototypic melts (VULCANO, FARO, COMAS) the important phenomena during spreading and the related physics are adequately understood. An important observation is that multi-component corium melts spread, even if their initial temperature is below the liquidus temperature. Immobilisation of the melt occurs when a substantial fraction of crystals has formed during cool-down of the melt and increases the viscosity of the mushy melt to virtually infinity, or when a stable surface crust is formed at the melt front. Spreading on a concrete surface slightly reduces the spreading length. The presence of a shallow water layer has minor influence on spreading and no energetic melt/water interactions were observed. It is concluded that for existing plants with their narrow cavities, spreading is sufficiently homogeneous and the spread area likely covers the entire cavity. As such, spreadability is not an issue. However, the spread depth may be large so that the debris coolability is not assured.

To better characterise the spreading processes in future reactors with possibly larger surfaces (such as the EPR), the available experimental information should be evaluated and synthesised systematically with respect to the expected accident conditions. The spreading codes have made good progress in modelling and should be further validated by systematic use of relevant experiments. In addition, the effect of concrete ablation on spreading should be quantified. At the end of the validation process a blind pretest calculation of a representative corium spreading experiment is considered to be useful. Some of the modelling problems that were discussed during the meeting may, however, not be relevant for the EPR typical spreading process as higher masses and release rates are expected.

Relations derived from dimensional analysis can be used as guidance for the final state of the spreading process.

Corium jets falling into water under in-vessel conditions with jet diameters of three to 10 cm form a particle bed of 50 % or higher on a cake of unfragmented corium. Steam explosions with very low efficiency were observed only when triggered in some of the experiments. These results, however, cannot be readily extrapolated to ex-vessel scenarios because, e.g., of the eventually different melt composition and large subcooling of the water.

Under ex-vessel conditions, fragmented jets are considered to be possible which have a good potential to be cooled. In addition to the CROTOS and FARO tests, new experiments became available from the COTELS project, which also uses prototypic melts and includes UO_2, ZrO_2, Zr and steel under ex-vessel conditions. COTELS showed no occurrence of spontaneous steam explosions similar to FARO and KROTOS. However, multiple jets and the influence of a driving gas pressure were presently not considered. Furthermore, the release of steam and eventually of hydrogen upon quenching of the melt is a point of interest for the containment atmosphere. The mechanisms of hydrogen production from purely oxidic melts during quenching as observed in FARO tests, deserves further consideration to clarify the details of corium-water interaction.

The closure of the FARO test facility leaves unresolved ex-vessel aspects and limits further investigations to the smaller KROTOS facility which is being transferred to CEA’s Cadarache Centre. It is recommended to focus the future programme on ex-vessel conditions.

Besides corium jets falling into water, COTELS also cover the process of ex-vessel melts being flooded from the top. These tests, which involved collapsed corium heights from 7 to 13 cm (close to 15 cm in the MACE M0 test), for the first time, indicated complete corium coolability by formation of a particulate debris bed, in contrast to the MACE experiments which showed only limited coolability for higher melts. The phenomena which influence the coolability process, such as particulate debris bed formation, crust break-up, and melt ejection from the top of the melt pool driven by gases from the decomposing concrete should be investigated in further detail. Although the final stop of concrete erosion is not assured, top flooding of the corium melt during melt concrete interaction could be beneficial during the late phase of an accident, e.g., for fission product retention. The consequences on further important implications for long-term accident management strategies, e.g. due to steam release and pressurisation of the containment, must be considered.

For the flooding, no occurrence of a steam explosion was observed in the MACE, COTELS, and KATS experiments with stratified geometry.

In the COMET bottom flooding concept, water is supplied to the bottom of the melt either by injection holes or by a porous concrete layer. Experiments have shown rapid and complete solidification mainly by creation of a porous structure of the freezing melt, which allows easy flooding by the steam-water coolant flow. The principle of the concept is further investigated using transparent simulant materials to show the coupling of water ingression, fragmentation and solidification. The bottom-cooling concept is a promising alternative and can be readily extrapolated to reactor scale. It is applicable to future reactor designs and potentially to some existing reactors. The pressurisation of the containment by steam is, however, a consequence, which must be considered.

The physico-chemical properties of the corium melt are essential for understanding and modelling of melt behaviour. The liquidus-solidus temperatures for U-Zr-O melts with compositions typical for BWRs and LWRs were measured. This is a necessary extension and confirmation of existing phase diagrams. Viscosity measurements were also presented for these melts above and below the liquidus temperature, and show variation over several orders of magnitude depending on the composition and temperature of the melt. These data are very important to describe physical processes in which solidification is involved. To estimate the viscosity of multicomponent oxide melts also in their freezing range, a model has been proposed. Further measurements are recommended, especially in the freezing range, with inclusion of Fe and Si oxides in the melt. Additionally the influence of other components (e.g., Pu in the case of mixed oxide fuel) on phase diagrams should be estimated, if the components are expected to have significant influence on melt properties.

Another important issue to be addressed is the mechanical stability of a corium crust under thermo-mechanical loading. This is particularly relevant to stop melt spreading and also for coolability investigation under top flooding condition where coolability would be improved if the crust can be breached thereby providing a path for water ingression.

Thermomechanical stability of ZrO_2 -ceramics and –concretes to resist the corium melt was investigated and conditions for stable long-term retention proposed with respect to temperature gradient and oxygen potential in the melt. Differences in various models regarding the influence of temperature and oxygen potential/diffusion on the dissolution process were noted and shall be clarified. For the EPR melt stabilisation concept, the authors concluded that all requirements on the stability of the protective layer can be fulfilled. Confirmation is expected from the large-scale CORESA tests.

Finally, applications to reactor plants were presented. In the framework of Spanish PSAs, MELCOR application highlighted the ex-vessel corium coolability issue. The very wide range of containment failure probability, which is related to the uncertainty of ex-vessel debris coolability, confirmed the need for further studies of ex-vessel coolability.

The GAREC group has analysed ex-vessel corium recovery for some present and future PWRs. This includes scenarios for core meltdown and corium transfer to the lower head, corium behaviour in the lower head, vessel failure, risk of steam explosion, corium-concrete interaction and coolability, corium spreading and accumulation, corium ceramic interaction, and long-term corium stabilisation. The various aspects were partly discussed in the proceeding issues.

Experimental and theoretical analysis on two-phase flow heat transfer in large scale was presented, as it may occur after surface flooding of the melt. Stable and oscillating flow conditions were observed depending on the degree of subcooling of the coolant water.

A detailed analysis of the EPR ex-vessel melt retention concept was also presented. This includes the temporary retention of the corium melt in the reactor pit to make corium recovery independent of various scenarios, the fast release of the corium to the spreading compartment, and the cooling by surface flooding. A cooled protective layer stabilises and cools the bottom of the corium melt. This EPR concept has triggered much of the research, which was discussed throughout the meeting.

Conclusions and Recommendations

The following conclusions and recommendations are formulated after evaluation of the presentations and discussions. They are generally listed in the sequence of the meltdown process.

(1) The conditions of melt release at vessel failure may vary according to the variations of core melt-down in the RPV. Relevant scenarios and bounding melt release conditions, such as melt dispersal into the containment as one extreme or jet impingement as another extreme release mode, should be quantified in order to plan and assess different management procedures or countermeasures for accident mitigation.

(2) The phase diagrams and physical property databases to characterise corium melts of various compositions should be extended, especially with respect to lower melt temperatures and in the freezing range.

(3) During solidification of the corium melt or during its interaction with structure materials, thermal-hydraulic processes related to heat transfer and movement of the melt are closely coupled to physico-chemical processes which change the constitution of the multi-component melt and its physical properties. The coupled modelling of these processes should be further developed, especially with respect to its implementation into large computer codes.

(4) Ex-vessel melt cooling by melt release into the flooded reactor cavity and resulting in major fragmentation should be further investigated, including possibly negative consequences as e.g. steam explosions.

(5) The effectiveness of cooling a corium pool by top flooding should continue to be further investigated. Key issues are particulate debris formation, melt ejection, and crust break-up as potential mechanisms for long-term debris coolability.

(6) Investigations and development of the bottom flooding concept should continue as an alternate cooling concept, including the use of porous, water filled concrete. The concept is attractive for future reactors and potentially for some existing plants.

(7) Substantial information about the spreading of corium melts is available in form of experiments and computer codes. This information should be condensed and, where necessary, completed to predict the melt conditions for which sufficient melt spreading under reactor conditions can be expected also for large areas as proposed for future reactors. A blind pretest calculation of a representative corium spreading experiment is considered to be useful.

(8) For the evolutionary containment concept of the EPR, an ex-vessel corium stabilisation concept was proposed and will be subject of the licensing procedure. Where necessary, investigations into the safe performance of this concept should continue.

(9) Melt cooling by direct water contact has important consequences on containment processes, such as pressure build-up by steam release, hydrogen concentration and fission product distribution. These processes should be further quantified for individual plants to asses the various aspects of accident management procedures.

ANNEX I

PROGRAMME COMMITTEE OF THE WORKSHOP AND SESSION CHAIRMEN

Programme Committee:

H. Alsmeyer (Chairman)	Forschungszentrum Karlsruhe, Germany
H.-J. Allelein	Gesellschaft für Anlagen- und Reaktorsicherheit, Germany
S. Basu	U.S. Nuclear Regulatory Commission, U.S.A.
J.-C. Latché	Centre d'Etudes de Cadarache, IPSN, France
J. Sugimoto	Japan Atomic Energy Research Institute (JAERI), Japan

Sesssion Chairmen:

H.-J. Allelein	Gesellschaft für Anlagen- und Reaktorsicherheit, Germany
H. Alsmeyer	Forschungszentrum Karlsruhe, Germany
S. Basu	U.S. Nuclear Regulatory Commission, U.S.A.
G. Cognet	Centre d'Etudes de Cadarache, CEA, France
V. Gustavsson	SwedPower AB, Sweden
J.-C. Latché	Centre d'Etudes de Cadarache, IPSN, France
H. Nagasaka	Nuclear Power Engineering Corporation (NUPEC), Japan
W. Scholtyssek	Forschungszentrum Karlsruhe, Germany

OECD/NEA:

J. Royen	OECD Nuclear Energy Agency

ANNEX II

SUMMARIES OF SESSION CHAIRMEN

SESSION A: SPECIAL MODES OF CORIUM DISCHARGE INTO THE CONTAINMENT

Session Chairman: Sudhamay Basu (NRC, USA)

Four papers in this session discussed research findings on special modes of corium discharge (e.g., low pressure melt ejection, jet impingement, etc.) into the containment and consequences of such discharge on ex-vessel debris coolability and containment integrity. The results of research are particularly applicable to EPR-type cavity designs though some results can also have potential applications to current generation reactors.

Experimental investigation of corium discharge at low system pressure (<2 MPa) was reported in the first paper. The objective of the DISCO-C series of experiments at Forschungszentrum Karlsruhe (FZK) was to determine the upper bound of the RCS pressure that would result in minimum melt dispersal out of an annular cavity (e.g., EPR-type cavity design). Effects of breach size, location and failure pressure on dispersion were studied systematically using cold simulants (nitrogen/water or nitrogen/liquid bismuth alloy and helium/water). Experiments with larger holes showed more dispersal than those with smaller holes and produced higher peak pressures in the cavity.

Experiments with breach at the RPV bottom showed more dispersal than that observed in one experiment with a side breach. The threshold pressure for dispersion was found less pronounced in the annular cavity geometry than in cavities with non-annular geometry. However, more experiments are judged to be necessary, in particular, with side breach and hot simulants (e.g., thermite), before a definitive conclusion can be drawn about the optimum annular cavity design for minimum dispersal. Such experiments are planned in the current framework of activities.

During the discussion, it was clear that the results have important implications for EPR-type designs. Even though consequent direct containment heating from pressurised melt ejection is not considered a threat to EPR containment integrity, it is desirable to contain the ejected melt into a core catcher so that the inventory can be stabilised and rendered coolable. Also, for both EPR-type and operating reactors, dispersed melt trapped outside the cavity may degrade equipment and structural performance due to an imposed thermal load. Therefore, the present investigation has also implications for equipment qualification. The discussion further pointed to the fact that consideration of side breach is appropriate in the melt ejection investigation.

The second paper was an analytical complement of the first paper. The objective was to model the low pressure corium dispersal phenomenon with a computer code that combines the advantage of existing lumped-parameter models for system codes with the details of a multi-component transient fluid dynamics code. The underlying hypothesis for such code development is that the discharge of corium starts as a single-phase flow for which lumped-parameter modelling is adequate but later on, switches to a two-phase flow for which detailed multicomponent, multifield modelling becomes necessary.

The analytical work at FZK utilised the Advanced Fluid Dynamics Model (AFDM) code to track water, molten corium, and gas-vapour mixture in two dimensions. Models were added to the AFDM code to describe melt oxidation and hydrogen combustion, as well as hydrodynamics of liquid films. Calculated dispersion rates using the code were found to be sensitive to transition time from the single-phase to two-phase. Comparison between measured (DISCO-C experiments and two SNL thermite experiments) and calculated dispersion rates showed reasonably good agreement given the early stage of code development.

During the discussion, it was clear that important dispersion processes as well as factors affecting dispersion (e.g., hole ablation, freezing, etc.) need to be considered in the code. Furthermore, it was noted that the steady-state entrainment model might not be fully valid when dealing with a transient process. Further code development addressing the above deficiencies was recommended.

Experimental investigation of corium jet discharge at low system pressure and the impingement of jet on substratum materials was the subject of the third paper. Research reported in this paper investigated corium jet interaction with sacrificial silica concrete in the KAJET experimental program at FZK, designed to gain insights into long-term retention and cooling. Performance tests were carried out using water and thermite as melt simulants to obtain information on nozzle geometry and material for generating a compact melt jet. Also, two erosion tests were carried out with a melt jet, which was initially metallic and then changed to oxidic. Erosion depth of the substratum was found to be higher with metallic melt than with oxidic melt. More experiments are planned with parametric variations of substratum material, melt mass, driving pressure and nozzle diameter. Results will be used to support the selection of suitable substratum materials for EPR.

During the discussion, similar work by PNC in Japan and by KTH in Stockholm was noted. A comparison of different experiments with regard to heat transfer rates would be useful. Further, it was felt that scaling studies would be required for reactor applications of the findings. Such studies are in progress at the University of Bochum, Germany.

Another aspect of the core catcher concept, i.e., stabilising the discharged corium with a sacrificial layer before releasing it to a spreading area was the subject of the last paper of this session. The paper reported a series of KAPOOL experiments performed at FZK to investigate the erosion behaviour of a sacrificial concrete layer. Iron-alumina thermite was used as a melt simulant and two different sacrificial concretes were investigated, based on borosilicate glass, and iron oxide and silica. From the limited set of experiments (three each with the two concrete compositions) conducted thus far, it appears that the borosilicate glass has a lower erosion rate. On the other hand, the transient temperature behaviour of the thermite melt does not allow to discriminate between the influence of concrete type and oxidation of zircaloy which was present in two of the tests, and therefore further investigations may be necessary.

The series of KAPOOL experiments also investigated phenomena related to the failure mechanism of a steel gate, as featured in the current design of the EPR core catcher. It is important to ensure a sufficiently large opening cross-section of the steel gate under prototypic thermo-mechanical loading of the core debris. Experiments were conducted to investigate gate ablation in presence of both metallic (iron) and oxidic melts. Preliminary analysis of oxidic melt attack indicated fast temperature rise of the steel gate followed by formation of a crust. Subsequently, gaps formed between the crust and the gate resulting in large resistance to heat transfer.

During the discussion, the proof of a sufficiently large opening during gate failure was viewed by some as the most uncertain issue in the overall melt retention scheme of the EPR design. However, it relates to the design issue and those involved in design expressed confidence that the gate could be designed to melt through providing the desired opening. Further work to resolve the issue of gate meltthrough should be identified.

In the summary discussion of all four papers on special modes of corium discharge, important contributions of the FZK research team was recognised, particularly with regard to the relevance of research results to EPR-type reactor designs. The results provide important data on initial and boundary conditions for further investigation of long-term coolability and retention of core melt in the EPR design. Some results can also have potential applications to current generation reactors. In order to obtain bounding data for reactor applications, a few recommendations were formulated. It was recommended that with respect to RPV failure, consequences of a side breach be investigated further as an important failure mode. Scaling studies were recommended to extrapolate the results of small-scale simulant experiments to reactor prototypic cases. Finally, the important role of physico-chemical processes was identified as an area requiring careful studies.

SESSION B: PHENOMENA TO ACHIEVE COOLABILITY

Session B1: Natural Convection Heat Transfer With Bubbling

Session Chairman: Veine Gustavsson (SwedPower AB, Sweden)

This session consisted of three papers. The first paper dealt with heat transfer experiments from internally heated pools with and without gas injection, investigated in the BALI facility in Grenoble. The objective of this work was to quantify heat transfer coefficients at pool boundaries considering the effects of viscosity and superficial gas velocity. Water was used as corium simulant in the experiments and different weight fractions of cellulose were added to vary the viscosity. The dimension of the test section was about 3m long, 0,5m high and 0,15m wide. The single-phase tests include three different cooling conditions and each test was performed for three pool viscosities. These experimental results agree well with the correlations in the literature (e.g. Reinecke and Steinberner).

The multiphase tests were performed with gas injection through the bottom ice crust with superficial velocities in the range 1 cm/s to 20 cm/s. Three different pool viscosities were investigated. The measured heat transfer coefficients, especially as influenced by the viscosity of the pool, are not correctly represented by existing correlations and large differences exist between published correlations. With respect to MCCI configurations it is concluded from the experiments that for superficial gas velocities greater than 0.5 cm/s, as e.g. existing in the MACE M3B experiment, the power split of the heat flux to the upper surface referred to the total internal heat generation is 50 % and does not depend significantly on superficial gas velocity or on pool viscosity because the bulk of the pool is well stirred.

In the development of models in this work, the coupling of thermal-hydraulic and physico-chemical effects was taken into account. The correlations derived from the BALI experiments have been used in the simulation of ACE and MACE experiments. This work was presented in the last paper of Session B1.

The second paper in Session B1 discussed the effects of solid particles on heat transfer in multilayered liquid pools with gas injection. This work reported experiments performed at University of Wisconsin in the US. In the experiments two fluid layers were used consisting of an upper oil layer and a lower layer of water or glycerin. Solid particles of polystyrene beads were added to the lower layer to simulate the solid and liquid slurry which may eventually form when the corium melt cools below the liquidus temperature. The addition of the beads in many cases lead to the agglomeration of a quasi solid layer at the interface between the two fluids. On this situation the report was focused.

It was observed that the viscosity of the fluid in the pool had a dominating effect on the heat transfer coefficients to the upper and lower boundaries. It was also found that the solid fraction in the pool did not have a first order effect on the heat transfer coefficient. Special attention was given to the power split of the up/down ratio, which may strongly vary according to the boundary condition. It is concluded that existing models and correlations must be used with caution.

The last contribution in Session B2 was about simulation of ACE and MACE experiments on molten corium/concrete interaction using a phase segregation model which was implemented in the TOLBIAC code. The phase segregation is related to solidification of refractory components UO_2 and ZrO_2 in the low temperature zone near the corium/concrete interface. This process changes the composition of the residual liquid melt.

Three components were taken into account to characterize the melt: oxides, metals, and gas, and the following phenomena were included: metal/oxide stratification, residual power, free surface heat transfer, and crust formation.

Comparison of experimental data and calculations with the phase segregation model gives a better understanding and description of late corium/concrete interaction when components of the melt start to solidify.

There are several points in favour of the phase segregation approach for MCCI:

- the temperature traces can be recalculated, even during interaction transients;
- the material effects on melt temperature are explained;
- the effect of power variation on melt temperature is well predicted;
- the post test examinations show strong variations in melt composition;
- the composition of melt ejected in the MACE experiment M3B could be well calculated;
- the approach offers a possible explanation of periodic bursts of the crust during the test;
- the temperature-viscosity contradiction is resolved.

The confirmation of this approach is subject of ongoing analytical and experimental work e. g. in the EC funded ECOSTAR program.

SESSION B2: CHARACTERISTICS OF PARTICLE BEDS

Session Chairman: Veine Gustavsson (SwedPower AB, Sweden)

Session B2 consisted of three contributions.

The first paper described the characterisation of debris bed generated by FCI. This work was done at Professor Sehgals group at RIT, Stockholm.

In the past many investigations have been done to characterise the size distribution of particles from a debris bed generated by FCI. In the work at RIT, four types of statistical distributions were applied, namely: Weibull, log-normal, upper limit log-normal, and a distribution that resulted from the sequential fragmentation theory (SFT) from Brown. Data from experiments were fitted to each of the distributions. Two sets of data were used in this work: one set from the JRC/Ispra, KROTOS experimental program and the other set from the MIRA-20L program at RIT.

It was found that the SFT (sequential fragmentation theory) worked best. SFT is based on two parameters: mass mean diameter and a fractional dimension related to the shape of the particles.

A conclusion from this work is that the size distribution in a debris bed generated by fuel coolant interaction can be fitted to the SFT distribution, where the fractal dimension varies between two and three for the data analysed.

The second contribution in Session B2 was about an experimental investigation on dryout heat flux of a particle bed with a downcomer. Also this work was performed at RIT in Stockholm.

Many experimental and analytical studies exist world-wide which investigated the dryout heat flux in a debris bed cooled with top flooding. Important results have been achieved, which show that the coolability of the debris bed depends strongly on particle size, shape and porosity distribution, and beds with small porosity are more difficult to cool than those with large porosity. For stratified beds, the layer on the top, where smaller particles tend to accumulate, will determine if the bed is eventually un-coolable. However, the possibilities for coolability will be improved if water is supplied at the bottom of the debris bed via a downcomer.

Two series of experiments were performed on the dryout heat flux in the POMECO (POrous MEdia COolability) facility. One was with homogenous beds and the other one with stratified beds. The porosity of the particle beds was varied from 25 to 40% and the average particle size from 0,2 to 1,0 mm. The material used in the test was made of different sand particles.

For the stratified beds the smaller particles were accumulated on the top of the bed, and dominated the dryout process.

The effect of downcomers on coolability was investigated both for homogenous and stratified beds. It was found that downcomers enhanced the dryout heat flux substantially- in the experiments in the range from 50 to 350%.

The last contribution in Session B2 was an experimental investigation on particulate debris bed coolability in a multidimensional configuration. This work was performed by EdF. The experimental program is called SILFIDE, which is a French acronym for “simulation of fragmented debris with internal heat generation”.

The purpose of SILFIDE is to provide data on multidimensional configurations taking into account natural circulation due to the gravity difference between liquid and vapour phase. In the experiments, corium is simulated by steel spheres heated by electrical induction heating. Water is used as coolant. The dryout heat flux is measured for different geometrical configurations and the heatup of the bed is recorded.

The experimental program is still in progress. First experiments were reported. The heating of the particle bed may, however, be not sufficiently uniform to draw conclusions at the present stage When the data for two-dimensional homogenous beds are completed, more complex heterogeneous configurations will be investigated in the SILFIDE facility.

SESSION B3: SPREADING

Session Chairmen: H.-J. Allelein (GRS, Germany), J.-C. Latché (IPSN, France)

This session was devoted to the problem of melt spreading. Twelve papers were presented, covering experiments, code development and code validation by reactor applications.

The first presentation gave a general survey about the experimental activities (RIT and KATS simulant material experiments, FARO and VULCANO using real material) and analytical ones (improvement and validation of the spreading codes CORFLOW and THEMA) performed in the CSC-Project of the 4th European Framework Programme. Most of this work was presented in the following papers in more detail.

The next four presentations mainly dealt with the experimental findings in the test series KATS (FZK), VULCANO (CEA), COMAS (SNU), and FARO (JRC). As a result of these experimental programs and, more generally, of the experimental work performed in Europe, a wide range of data is now available :

- from low (CORINE), medium (RIT) and high temperature (KATS) simulant experiments to real material tests (VULCANO, FARO, COMAS);

- with varied inlet conditions : low and high flowrate, temperatures ranging from below melt liquidus to large superheat;

- with inert or concrete basemat.

Melt masses spread in these experiments are generally lower than 300 kg. Masses up to two tons were spread in the COMAS experiments. These are still lower than in reactor accident situations, where melt masses of 100 tons and higher are considered. The main experimental results are:

- The inflow conditions (initial melt temperature, mass and composition of the melt, pouring rate) have a major influence on the spreading process.

- Different observations about the influence of the substratum material have been made in the COMAS and KATS experiments. In COMAS, no significant difference between 1D spreading on concrete and ceramic material was seen. This effect may be explained by the high pouring rate and the resulting short spreading period realised in the COMAS experiments.

- In contradiction, the one-dimensional KATS experiments 12 and 13 have shown a significant difference in the spreading length of about 30%. The shape of the area covered with melt is also totally different in the two-dimensional KATS experiments 8 and 17. Nevertheless, in both cases about 60 % of the surface are covered with melt.

- Following the KATS observations, the influence of an epoxy paint on a concrete surface is of minor importance for the overall spreading behaviour of the bulk of the melt.

- Only experiments with a shallow water layer (up to 1 cm) initially present on the spreading surface were performed. In all these experiments using prototypic material, only one minor energetic melt-water interaction happened. In addition, the presence of this film of water seems to have only minor influence on melt spreading.

- The porosity of the spread material after cooling was in some cases high (VULCANO) and in other cases low (COMAS, FARO). The reason for this high porosity has to be clarified as well as the occurrence of surface cracks of the solidified melt found in many experiments.

- In the COMAS and VULCANO series, the authors observed good spreadability even for oxidic melts which spread with temperatures significantly below the liquidus temperature.

- In the COMAS series it is reported that during the spreading process mixed melts separate into metal and oxide layers. .

After the presentations about these four experimental series, five presentations were given about the spreading codes CORFLOW, CROCO, LAVA and THEMA. These codes are based on a different modelling of the spreading process:

- LAVA and THEMA solve the mass, momentum and energy balance equations integrated over the flow height ; this approach reduces the 2D- or 3D-problem to, respectively, one or two (horizontal) dimensions. In LAVA, inertia forces are neglected.

- CROCO solves the 2D (one horizontal, either cartesian or axisymmetric, and the vertical dimension) Navier-Stokes equations, either without any additional assumption or using the momentum balance simplifications arising from the thin flow approximation.

- CORFLOW solves the 2D- or 3D-Navier-Stokes equations.

LAVA, CROCO and CORFLOW are able to take into account Newtonian or non-Newtonian (Bingham) rheological laws.

The following conclusions are drawn from the calculations:

- The major part of the calculations presented was in rather good agreement with experimental data. Remaining discrepancies, which are identified in comparison with experiments, may be partly attributed to experimental uncertainties, such as initial conditions or material properties. Some models in the codes require further qualification, which should be achieved by verification through characteristic experiments. Improvements should concentrate on those phenomena, which are of primary importance for the spreading process of large melt masses in reactor scale.

- The actual understanding of the melt stabilisation process is that the stopping might be due to the growth of a low temperature, highly viscous boundary layer at the leading edge. None of the codes presently simulates the mechanical stability of the front crust, but all of them take credit from rapid increase of the viscosity (or the yield stress) near the freezing temperature.

The great number of calculations performed with these different codes, including a few sensitivity analyses, lead to the requirements of:

- a sufficiently qualified database of material properties with special respect to the viscosity and, possibly, the yield stress, of the liquid phase,

- a high accuracy of the experimental data concerning inflow boundary conditions (temperature and mass of the melt as well as mass flow rate).

EPR spreading calculated with CORFLOW was also presented. In the calculations, different assumptions about the initial mixing or stratification of the melt phases in the pit were made. In addition, material properties of the oxidic phase, the corium initial temperature, the flow area of the sacrificial gate, and the rheological behaviour of the melt (Newtonian to Bingham) were varied. All these different calculated cases lead to an almost homogenous corium layer thickness in the completely covered spreading area in less than 60 s. But it has to be stated that some of these computations have been performed with high melt overheat, and the mass flow rates correspond to a high gate cross section of 2.4 m^2 with the exception of one calculation for 0.24 m^2 opening.

After the code presentations, a method based on dimensional analysis was presented to assess spreading characteristics. This method from RIT was first developed for spreading in one-dimensional channels and has then been extended to spreading into an open area. In the discussion about this method, a suspected discrepancy in the theoretical assumption was discussed, which remains to be clarified.

In the last presentation, which dealt with the remelting of immobilised melt pile-ups, results obtained with a two-domain approach on moving adapting grids for the convection dominated melting problem with internal heat sources were shown. In all cases a strong convective mixing and cooling was calculated, so the temperature distribution in the liquid phase is mainly isothermal. Crust melting was predicted to appear at the top of the dome. For the moment, turbulence is not taken into account.

SESSION B4: FRAGMENTATION AND QUENCHING

Session Chairman: Werner Scholtyssek (FZK, Germany)

A necessary condition to achieve efficient quenching, cooling and stabilisation of a high melt layer in a restricted geometry is fragmentation of the melt which provides for a high heat transfer area and for sufficient void inside the melt to allow circulation of coolant. In Session B4, the phenomena observed during melt injection into a coolant pool were discussed. In Session B5, the results of studies of flooding of a melt layer, either from the top or from the bottom, were presented.

Four papers in Session B4 presented results that were obtained in the research area of fuel-coolant interaction (FCI). The results which are of primary interest under the aspect of coolability are:

- the fragmentation of a melt jet,
- the particle size and size distribution,
- the quenching rate and
- the final debris bed configuration.

Other interesting results are

- the hydrogen production during fragmentation and quenching,
- the probability of occurrence of a steam explosion and
- the thermal and mechanical loads to structures.

In the first paper, an overview of the FARO and KROTOS programs was given, including implications on FCI. Corium melt jets of 30 mm to 100 mm diameter were injected into water pools of variable height. The tests were mainly performed under in-vessel conditions, i.e. high system pressure and saturated water. Some tests were done under ex-vessel conditions, i.e. low pressure and subcooled water. UO_2-ZrO_2 melt was used, with addition of metallic Zr in one FARO-test. In all tests with pure oxidic melt, about 50% of the melt was fragmented. Complete fragmentation occurred in the test with metallic Zr. The final debris bed consisted of a solid "cake" at the bottom, overlaid by particles with mass averaged diameter of $2{,}5 < d < 5$mm. No steam explosion occurred in tests without triggering, and in those tests where steam explosion occurred, the efficiency was very low. Significant production of hydrogen was observed also in those tests with pure oxidic melt.

The second paper described modeling of coarse break-up of molten core jet. The model is part of the JASMINE code which intends to simulate FCI. It describes jet penetration into coolant, production of melt particles and their movement in the pool, and melt pool formation at the bottom. For treatment of thermal-hydraulics of the coolant, a coupling to the 3-D two-phase flow code ACE-3D will be made. The numerical behaviour of the model was tested by comparison with an analytical case. Further, the experiment ALPHA-MJB (MJB: melt jet break-up) was analysed. Reasonable agreement could be achieved after adjustment of certain model parameters. Further assessment of the parameters will be performed.

Paper 3 gave an overview of the COTELS project that started in 1995. Paper 4 described FCI tests under ex-vessel conditions within this project. COTELS is a common experimental project of Japan and Kazakhstan research organisations, oriented to FCI and MCCI. The testing complex, located in Kazakhstan, includes three experimental facilities, “SLAVA”, “LAVA” and “LAVA-M”. Corium with mass up to 60 kg and with composition UO_2-steel-ZrO_2-Zr is used, with temperatures up to 3200 K. The melt is produced in an electric induction melting furnace. To simulate decay heat, induction heating is also provided for the crucible in MCCI tests.

In the FCI tests, melt jets of 50 mm diameter were dropped into water pools of variable height and temperature. In all tests, nearly complete fragmentation of the melt occurred. Steam explosion was not observed. It was found that the first pressure peak could be correlated with the mass median diameter of the fragmented corium particles. The correlation holds also when FARO tests are included in the analysis.

SESSION B5: FLOODING

Session Chairman: Werner Scholtyssek (FZK, Germany)

The phenomena observed during flooding of a melt layer with water, either from top or from bottom, were addressed in 7 presentations in this session. Results of primary interest concerned:

- physics, chemistry and material properties important in MCCI and flooding processes
- quenching characteristics;
- final debris configuration;
- thermal and mechanical loads.

Other interesting results were:

- probability of steam explosion
- H_2-production
- source term related phenomena.

In the first paper, ex-vessel debris cooling tests performed within the COTELS-project were described. The LAVA-M facility was used with two types of concrete crucibles with different aspect ratios. The corium melt with mass of about 60 kg and temperature of about 3200 K was dropped into the crucible which could be induction heated to simulate decay heat. 8 to 10 min after the drop water was injected at a rate of 2 l/s onto the top surface of the melt. No steam explosion was observed in 10 tests. Although fragmentation of the debris beds was not complete, and in some tests solid "ingots" were observed, cooling of the melt was achieved in all cases. This was partly attributed to formation of cracks and channels in the corium and in the concrete around and below.

The second paper reported results of structural investigation of the COTELS tests and comparison with other tests (WETCOR, MACE). Especially the absence of adhesion of the top crust to the side walls was mentioned, which helped, together with concrete erosion and formation of rubble in side walls and bottom concrete, to reach coolability and to stop concrete erosion. The particle size spectrum was analysed and found to correlate well with the Rosin-Rammler-equation.

In the third paper, an overview on the MACE test program performed at Argonne National Laboratory was given, and especially results of tests M0 and M1b were presented. The tests address the coolability - by water addition from above - of corium being in interaction with concrete. Crucibles of different cross sections and melt masses from 100 to 2000 kg have been used. The melt is heated by direct electrical heating. In all tests, crust formation and anchoring of the crust to the crucible side walls and formation of gaps between crust and the molten corium below led to significant reduction of the heat flux to the water on top so that complete quenching of the melt could not be clearly demonstrated. In prototypic, large caverns, however, the crust would very probably float on top of and remain in contact with the melt, and therefore heat transfer mechanisms identified in the tests could lead to coolability. This will be further investigated in separate tests which should increase the database in support of model development and validation activities.

The fourth paper presented the CORQUENCH model that was developed at Argonne National Laboratory to calculate corium coolability. The modeled heat sources and sinks include decay heat, chemical reactions, heat transfer into walls and to the overlying atmosphere (gas or water). Options for 1-D and 2-D application are implemented. The model was validated on ACE/MCCI and MACE tests with reasonable success, when crust permeability was assumed. Scoping calculations for representative plant conditions showed, that, compared to the dry case, concrete erosion is significantly reduced by water addition and possibly arrested if dryout limits exceed 200 kW/m^2.

Papers five and six presented results of the COMET and COMET-PC investigations that were performed at Forschungszentrum Karlsruhe. The COMET concept proposes spreading of the melt and quenching by water injection from the bottom. This is achieved by erosion of sacrificial concrete until a system of water-bearing channels (COMET) or porous, water-filled concrete (COMET-PC) is reached. Within the program, a great number of transient tests and tests with decay heat simulation have been performed on different scales using thermite as simulant for corium. Upon passive opening of the channels, evaporating water fragments the melt and provides the conditions for rapid and efficient quenching. Tests at ANL with prototypical corium confirmed the observations. No energetic interactions of melt with water were observed; this can be attributed to the limited amount of water available at any time. High fragmentation of the frozen melt guarantees long-term stabilisation and coolability. Consideration must be given to the pressure increase in the containment because of steam production during the quenching process.

The final paper presented results of experiments performed at the Royal Institute of Technology (Sweden) to study details of the quenching process during bottom flooding. Coolant was injected from the bottom into simulant melt, for which non-eutectic oxidic salt mixtures were used for high temperature tests, and paraffin oil for low temperature tests. The latter allowed direct visual observation of the processes. The porosity formation was studied depending on parameters including melt height, melt superheat, coolant inflow rate and pressure, and number of coolant nozzles. Important parameters governing the fragmentation process were identified to be melt viscosity, the temperature difference between melt and coolant, and the flow rate.

DISCUSSIONS ON SESSIONS B4/B5

Concerning melt injection into water, it was stated that a significant database has been established. However, for ex-vessel situations some additional data would be needed. Also, geometric as well as material scaling considerations deserve more consideration. From the presently available data one can conclude that significant fragmentation of the melt is likely to occur when a melt jet is injected into water. The debris configuration in the cavity consists of a melt cake at the bottom and particulate debris on top, which may form a coolable system. Steam explosion is not likely to occur with corium material. However for confirmation of this observation it would be necessary to put the differences that are observed between thermite and corium behaviour in the FCI process on a quantitative and mechanistic basis. As a consequence of the observations, cavity flooding before RPV failure as an accident management measure was generally considered to be beneficial.

In view of coolabity of a debris bed by top flooding, encouraging results have been obtained. It was shown that under favorable conditions coolability can be reached. However, the differences in the experimental findings on coolability in the COTELS and MACE experiments require further analysis. In any case, a benefit from water addition can be expected because erosion of the underlaying concrete layer would be slowed down and FP release would decrease. The risk of steam explosion in such a configuration was considered to be small. An enriched database that could be used for modelling and upscaling of related phenomena could help to confirm the findings.

The concept of bottom flooding of the melt was generally considered as very effective for quenching and stabilising of the melt. A core catcher based on this concept can provide a reliable solution for future reactors and possibly for some existing ones. A better understanding of the processes of fragmentation, debris formation, heat transfer and fission product behaviour could help to widen safety margins even further.

SESSION C: MATERIAL PROPERTIES AND THERMOCHEMISTRY:

SESSION C1: PROPERTIES

Session Chairman: Gérard Cognet (CEA, France)

The list of physical and thermodynamic properties which play a role in corium progression during a severe accident is quite impressive: liquidus and solidus temperatures, enthalpy, density, viscosity, thermal conductivity, emissivity, surface tension. Moreover, most of these properties vary significantly with the composition and/or the temperature of the mixture. However, their importance not being equivalent, a prioritization can be made. Thus, the knowledge of phase diagrams and apparent viscosities is of utmost importance for the description of ex-vessel corium behaviour and cooling.

Three papers were presented in this session, one devoted to the determination of the liquidus and solidus temperatures of $(U, Zr)O_{2-x}$ mixtures, with various oxygen contents reflecting various stages of zirconium oxidation, and 2 devoted to the estimation of corium mixture viscosity.

The solidus and liquidus temperatures of various PWR and BWR corium mixtures were measured by ANL, using a Differential Thermal Analysis technique (DTA). For PWR corium compositions (U/Zr molar ratio of 1.64), the solidus temperature was found to increase from 2005°C at 30% Zr oxidation to 2105°C at 70% oxidation. The liquidus temperatures for these compositions were nominally 400°C higher, ranging from 2465°C at 30% Zr oxidation to 2520°C at 70% Zr oxidation. For BWR compositions (U/Zr molar ratio of 0.69), the solidus temperatures were found to increase from 1930°C to 2042°C as the Zr oxidation increased from 30 to 70%. The liquidus temperature for these compositions was found to be a function of oxidation level, ranging from 2198°C at 30% oxidation to 2475°C at 70% oxidation. These 2 data sets indicate that both the liquidus and solidus temperatures decrease with increasing Zr content in the melt. Post-test analyses indicate also that Zr is soluble in the oxide phase within the range 30 to 70% oxidation.

Questions from the audience showed that some discrepancies exist between the presented values and those predicted by GEMINI / TDBCR ; Further investigations are needed.

ANL measured the apparent viscosities of some typical BWR and PWR corium compositions by measuring the spreading rate in a 1D channel. The corresponding viscosity was estimated from the analytical solution given by Huppert for the spreading of isothermal free surface flows. Tests were conducted with compositions representative of Zr oxidation of 30, 50, and 70%. Data indicates that at a roughly constant temperature of 2500 °C, viscosity increases by approximately one order of magnitude for PWR compositions and by as much as three orders of magnitude for BWR compositions. At the highest Zr oxidation state considered (i.e. 70%), there is evidence that the increased viscosity is due to the development of a solid phase within the melt as a result of the melt temperature falling below the liquidus temperature.

Questions from the audience highlighted the following points:

- The accuracy which is sometimes poor and which depends on the realisation of isothermal conditions during tests;
- The use of this method to measure the apparent viscosity in the solidification range.

A general methodology, presented by the CEA, has been thoroughly investigated to calculate apparent corium mixture viscosities. This methodology, which extends the model initially, proposed by Seiler and Ganzhorn (1997) is based on three main steps:

- The determination of melt compositions and phases (solid and liquid) versus temperature using a thermodynamic computer code;
- The use of either the Andrade model or the Urbain model to calculate the viscosity of the remaining liquid phase versus temperature depending on the SiO_2 content;
- The use of a modified Arrhenius law to calculate the apparent viscosity in the solidification range.

This methodology has proved its efficiency by recalculation of the evolution of the viscosity of various mixtures, in particular those of a basalt with 18% UO2 content and those of a 50% corium - 50% concrete mixture. However, complementary measurements are needed to check its validity for any corium - concrete composition. Questions were essentially oriented towards the modified Arrhenius model and its spectrum of validation. In fact, this model has been qualified on 2 types of metal melts and on 2 corium mixtures, one of which published by Skoutajan et al. (1979) and the other by Roche et al. (1993).

The general discussion which followed this session underlined some important points:

- For ex-vessel applications, other phase diagrams (U, Zr, Fe, O) and (U, Zr, Fe, Si, O) require more efforts to be made;
- Considering Mox fuel, phase diagrams with Pu could be needed;
- An effort has to be made to characterise crust stability;
- Suitable correlations or methodology should be developed for other properties such as thermal conductivity (liquid phase and crusts), emissivity and surface tension; however here, the priority is lower.

SESSION C2: THERMOCHEMISTRY

Session Chairman: Gérard Cognet (CEA, France)

This session was devoted to the study of the compatibility of various materials regarding long-term corium collection, stabilisation and solidification. Five contributions were presented, three of which described the results of corium ceramic interaction tests, one, from the CEA, proposed a model for solidification and the last, from Siemens, described, in detail, the physico-chemical aspects of the EPR core-catcher concept.

The spreading area of the EPR core-catcher consists of three layers of different materials (from top to bottom): sacrificial concrete, sacrificial iron layer and zirconia, each of which playing a specific role. These roles were explained in detail by Dr. Hellmann, from Siemens, who also presented the results of laboratory tests which demonstrated that the target of decreasing the initially high liquidus temperature of the melt down to 1800 - 1850°C could be reached. Dr. Hellmann further reported about experiments performed at Siemens Erlangen on the thermo-chemical stability of zirconia-based protective material in contact with steel melts. This contact mode is characteristic for the EPR melt retention concept since an interaction of the zirconia layer with oxidic melt is avoided by the addition of sacrificial material. Supported by a physico-chemical model and available knowledge in the field of metallurgy, he deduced that a zirconia protective layer is chemically stable against an EPR-type steel melt. According to his argumentation, the oxygen concentration within such a steel melt and thus the related FeO-activity remain safely below the corresponding threshold values for the formation of liquid ZrO_2-FeO phases and therefore chemical dissolution of the zirconia material cannot occur. The performed experiments confirm this dependence between FeO-activity and related extent of erosion. They also showed that at the current state of knowledge, the ZrO_2 ramming mass is one of the most promising application forms for the bottom refractory layer.

Questions from the audience pointed out that, before final conclusions, more realistic tests seem to be needed, which will be performed within the CORESA programme.

The experiments of corium ceramic interaction (two papers: NITI and CEA) showed that the ablation of the ceramic is limited and blocked by the temperature gradient in the ceramic layer. Two dissolution models were proposed, one by S. Bechta from NITI and one by K. Froment from the CEA. The first one is based on the assumption that the ablation rate is proportional to the undersaturation degree, the second one is more complex because the authors want to take more phenomena into account. A comparison between these 2 models showed that the dependency of the ablation rate to the ΔT is not the same; Clarification seems to be needed.

Based on their experiments and their model, the Russian team from NITI claimed that the zirconia concrete (ZC) is well adapted as a protective material for core-catchers. However, based on the CEA study, any dissolution of a ceramic layer would be stopped, provided that a cooling system allows a certain temperature gradient to be maintained.

Another paper of CEA discussed the possibility of ceramic attack by oxygen which migrates from an oxidic corium layer through an iron layer. These tests proved this possibility exists, but this attack is weaker than in the case of direct contact between corium and ceramic. A theoretical estimate gives the right order of the dissolution process and shows that dissolution can be avoided by reduction of the oxygen transfer. As regards the differences found on erosion rates by Siemens and CEA, it was agreed that a common meeting will be needed to discuss in detail this issue in order to reach a joint position.

A theoretical study performed by the CEA on late phase severe accident processes has shown the importance of a strong coupling between thermal-hydraulics and physico-chemistry during melt attack. This coupling leads to two important conclusions:

- Instead of a mushy zone the solidifying corium melt would form a layer of segregated refractory components at the cold boundary under thermal-hydraulic steady state conditions;

- The current computer codes, which describe corium solidification and interaction with concrete or ceramics, have to be reviewed.

A first experimental proof of the coupling has been presented, however more experiments are needed, in particular with a sufficient scale to enable thermal-hydraulic effects to develop; These are to be performed within the VULCANO programme.

This presentation and its consequences, in particular the coupling of chemical thermodynamic codes with thermal-hydraulic codes was debated in the final discussions of this session. Discussions also highlighted that R&D efforts have to be made on dissolution phenomena and gas sparging effect.

SESSION D: REACTOR APPLICATION

Session Chairman: Hideo Nagasaka (NUPEC, Japan)

The Session D consisted of six papers. The first paper dealt with Level-2 PSA for Spanish individual nuclear power plants (CSN). The second paper was devoted to summarization of open problems of EPR core catcher and the corresponding R&D (GAREC). The third paper considered two-phase flow with possible instabilities of a natural circulation cooling system in EPR geometry (FZK). The remaining three papers dealt with the design considerations of the EPR core catcher (Siemens-KWU).

CSN has conducted independent regulatory evaluations of Level-2 PSA for all NPPs in Spain, focused on ex-vessel corium coolability issues using the MELCOR code. The effect of wet cavity flooding on MCCI suppression and the possibility of basemat melt-through were surveyed. Very wide range of containment failure probability due to the uncertainty of ex-vessel debris coolability confirmed the necessity of further enhanced study of MCCI for existing NPPs. Pool depth and subcooling should be considered in cavity flooding accident management to evaluate ex-vessel steam explosion probability.

The GAREC Working Group presented its view on major open problems with emphasis on the ex-vessel retention concept of EPR. Corresponding R&D programs were summarised extensively. This paper included scenarios for core meltdown and corium transfer to the lower head, corium behavior in the lower RPV head, vessel failure, risk of steam explosion, corium-concrete interaction and coolability, corium spreading and accumulation, corium ceramic interaction, and long-term corium stabilisation. GAREC concludes that coolability during MCCI by surface flooding is difficult to demonstrate with the present knowledge. But better understanding and modelling of the behaviour of the corium melt in the freezing range would predict rather low viscosity of the residual melt instead of formation of a mushy zone. This would enhance melt ejection and thus improve corium coolability. - The main uncertainties for the EPR corium cooling concept are seen in the melt-through of the gate and the effects of late water injection.

Experimental and theoretical analysis on natural circulation and boiling induced convection related to the debris cooling after the corium is spread over the melt catcher have been conducted at FZK. It is shown that the decay heat can be removed from the flooded core by heat exchangers in the sump of the containment. Special attention is given to flow instabilities in the two-phase flow regime in the boiling induced mixed convection loop. The instabilities are caused by the transition from bubbly to slug flow by flashing phenomena. Stable and oscillating flow conditions were observed depending on the degree of subcooling of the coolant water, and a stability diagram correlates the occurrence of instabilities with the operational characteristics of the cooling loop. Analytical models consisting of six equations of the two-fluid model with the interfacial terms are expected to be validated against full height simulation in the SUCOT test facility .

Main conceptual features of the EPR melt retention concept and the designed countermeasures to several problems were well summarised by three papers of Siemens-KWU. The retention concept focuses on the temporary retention of the corium melt in the reactor pit to make corium recovery independent of various scenarios, the fast release of the corium to the spreading compartment, and the cooling by surface flooding. This EPR concept has triggered much of the research, which was discussed throughout the meeting. To achieve the required melt stabilisation and cooling, the following features are described and their role for the cooling process is explained: sacrificial concrete layer and melt plug in the reactor pit, transfer channel to the spreading room, spreading room with an initially dry sacrificial concrete layer. After complete spreading of the melt and erosion of the upper concrete layer, a sacrificial steel layer would be melted which safely separates the potentially aggressive oxidic corium melt from the zirconia layer underneath. The water cooling system under the zirconia layer would be activated after melt spreading, flood the surface of the corium melt, and keep the ZrO_2 refractory layer at low temperatures, so that no thermochemical attack of the refractory layer is expected. The EPR melt stabilisation concept was subject to various licensing discussions, and after some recent conceptual improvements, is considered by the industry as a sound technical solution with reasonable costs.