SUMMARY AND CONCLUSIONS

WORKSHOP ON
LARGE MOLTEN POOL HEAT TRANSFER

(CEN Grenoble, 9-11 March 1994)
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OECD

The Convention establishing the Organisation for Economic Co-operation and Development (OECD) was signed on 14th December 1960.

Pursuant to Article 1 of the Convention, the 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 current Signatories of the Convention are Australia, Austria, Belgium, Canada, Denmark, Finland, France, the Federal Republic of Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NEA

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. NEA membership today consists of all European Member countries of OECD as well as Australia, Canada, Japan, Republic of Korea, Mexico and the United States. The Commission of the European Communities takes part in the work of the Agency.

The primary objectives of NEA are to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

NEA works in close collaboration with the International Atomic Energy Agency (IAEA), with which it has concluded 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 scientists and engineers. It was set up in 1973 to develop and coordinate the activities of the OECD Nuclear Energy Agency 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.
FOREWORD

The CSNI Workshop on Large Molten Heat Transfer held at Grenoble, France in March 1994 was organised by CSNI's Principal Working Group on the Confinement of Accidental Radioactive Releases (PWG4) with the co-operation of the Principal Working Group on Coolant System Behaviour (PWG2) and in collaboration with the Grenoble Nuclear Research Centre of the French Commissariat à l'Energie Atomique (CEA).

The Summary and the Conclusions of the Workshop are attached. The Session Summaries were prepared by the Session Chairmen, the Conclusions by the Programme Committee of the Workshop (a list of members is given in an appendix).

These Conclusions were endorsed by PWG2 and PWG4 at meetings held in September 1994. CSNI has approved publication of the document in the series of CSNI Reports at a meeting organised in November 1994.
WORKSHOP ON LARGE MOLTEN POOL HEAT TRANSFER

Conclusions and Recommendations

1. The cooling of debris in-vessel by external flooding is a reasonable accident management objective. Studies for a number of plants are encouraging. However, the capacity to implement this as an accident management procedure will be plant dependent, and plant specific questions must be addressed in any assessment. This became clear from a number of scoping analyses presented at the meeting as well as from two integrated studies for the Lovisa and AP600 designs.

2. Besides the ability to flood around the vessel, the major parameter is the decay heat, which depends on the rating of the core and the timing when external cooling is required to be implemented.

3. To validate the strategy, a number of aspects need to be considered in addition to the steady state heat balance. These include early transient effects, both in-vessel, through jet enhanced heat transfer in-vessel, and ex-vessel, through the ability to establish nucleate boiling as the vessel cools. Current work in these areas is encouraging. Provided nucleate boiling is established on the outside of the vessel, it is necessary to confirm that there are no other failure mechanisms, including the effect of the mechanical loading during the transient. The long term heat sink for the upward heat flux needs consideration; it may be necessary to add water in-vessel to stabilise the degradation of in-vessel structures. Fuel coolant interactions, which were not discussed in detail at the meeting, need to be considered both in assessing energetic failure of the lower head during melt relocation into the lower plenum, and in considering the failure potential of the possible weakened lower head if water was to be re-introduced late in such a scenario. Clearly, if the cooling strategy was not proven to be successful with adequate certainty, fuel coolant interactions in the cavity, and other cavity phenomena, would have to be considered. The potential release of fission products from the molten pool needs to be considered as the pool may remain at a high temperature for a prolonged period.

4. The peaking factor (the ratio of maximum local heat flux to the average) found in experiments for heat transfer from the in-vessel debris to the sidewall is sufficiently low that except for high decay heat scenarios, homogeneous melt pools are likely to be coolable provided there is nucleate boiling on the outside of the vessel. However, more extended scenario analysis is required to ensure that this applies to the range of likely debris conditions. In particular, the possible separation of a metallic layer has been identified as a way of increasing the thermal loading at the upper edges of the pool, while steel boiling and oxidic debris in a metallic layer should also be examined. In the presence of zirconium metal and separation, long term retention of a melt may also depend on the chemical dissolution of the vessel at temperatures below the melting point of vessel steel.

5. New experimental data (COPO - a large scale slab simulation of VVER lower head geometry; UCLA data for a hemispherical vessel) related to heat transfer from molten pools are broadly consistent with those previously available, specifically with the data for upward heat transfer from Kulacki and Emara (COPO gives higher upward heat fluxes at the highest Rayleigh numbers), and with the more general data of Mayinger and co-workers, obtained in rectangular and flat, semicircular geometries. Much of the latter data were not published in English, but are available in German; they include studies of the combined effect of a molten pool and a falling liquid jet.
6. The phase structure of the melt will be important in determining its heat transfer properties, particularly the nature of any crust at the wall and the temperature reached by the melt. While the possibility was raised that phase segregation when there is a gap between the solidus and liquidus in the oxidic phase may modify heat transfer, this proved only to be a minor effect in simulant experiments. Confirmation that this is the case with prototypic oxide mixtures is desirable. More information is desirable on the effects of pool size on the side-wall peaking factor; COPO is the first experiment at large scale and shows only a small peaking of the sidewall heat flux. COPO also showed that for near isothermal boundary conditions the upward heat flux was greater than that to the sidewall for Rayleigh numbers approaching those of a melt pool in a reactor lower head; this result should be confirmed for other geometries.

7. The COPO data have been used to assess modelling codes based on computational fluid dynamics. While good progress has been made in this area, it was evident that considerable care is required to obtain mesh independent solutions and that the standard turbulence models require enhancements to match the experimental data. Further improvements depend on obtaining reliable data to underpin the development of the turbulence models. This was seen as part of a wider programme of work on turbulence models leading to the development of general models, which could then be tested for this specific application.

8. While it is desirable to have such detailed models, particularly for the interpretation of experiments (including confirmation that they are representative of reactor melt pools and considerations of scaling), they are probably not necessary for safety assessments. However, if because of low margins, they are required in a safety assessment they will need to be enhanced to take account of other uncertainties such as those concerned with the scenario (metallic layers, etc), and the physical properties of the melt. Provided the external cooling provides a sufficient margin over the decay heat production, relatively simple models should be acceptable.

9. To make optimum use of both the experimental data and the calculational models, it is desirable to have improved physical properties, particularly thermal conductivity, viscosity, and emissivity of the surface for prototypic material and various compositions over the full temperature range of interest.

10. There has been good progress on establishing the heat flux that can be removed by boiling on the outside of the vessel, and new experimental results (ULPU, CYBL) were presented in this area. The data available imply that, unless there is strong peaking on the sidewall, there is a good hope to obtain efficient heat transfer through the (thinned) vessel. The establishment of nucleate boiling on the outside of the vessel will be encouraged by early depressurisation (allowing cooling of the vessel from an initial temperature in the vicinity of that corresponding to minimum film boiling conditions at containment pressure) and by the presence of oxide layers on the outside of the vessel, which improves the prospects of rewetting.

11. Having established that large heat fluxes can be removed in experiments, it is necessary to consider the flow paths and flow recirculation in the plant. The critical heat flux will be plant specific, and the phenomena to be considered include the effects of large channels, low pressures, thick walls and inclined and curved surfaces. Experiments, such as those in the ULPU facility at Santa Barbara and the CYBL facility at Sandia are providing prototypic data of direct utility to the plant provided the pertinent geometric and boundary conditions are satisfied. These data and those from the SULTAN facility at
Grenoble, which is designed to obtain fundamental boiling data, are available for the development of a model for application to the plant. Preliminary work on calculational models for ex-vessel heat transfer was reported at the meeting. However, the CYBL experiments demonstrated the complexity of the phenomena to be modelled (an axisymmetric pulsing of steam from the base; break-up into bubbles; possible condensation, because of the static head and mixing of the water; flashing as the static head falls close to the top surface in this experiment).

12. The behaviour of the thermal insulation around the vessel needs to be considered; it may be possible to optimise this in future designs to maximise the heat removal by external boiling. The insulation should have sufficient rigidity to cope with the violent boiling observed in some experiments.

13. A number of new experimental programmes were discussed at the Workshop. In general their purpose is to improve the understanding of physical phenomena, confirm current hypotheses, provide new insights into physical properties and provide data for code validation. These experiments include the OECD/Russian RASPLAV project, which includes tests with heated pools of prototypic materials, besides property measurements of prototypic melts. Experiments with real materials are also under development by CEA (VULCANO), which is oriented towards validation of melt spreading and core catcher systems. Melt-spreading and melt-structure interaction tests have also been proposed as an extension to the FARO-LWR programme (which currently uses prototypic melts for melt-water interaction investigations). These are long term programmes, whose technical feasibility is under investigation, as is the development of new techniques, particularly for sustaining the heating in the melt in the appropriate geometry. Pre-test calculations make an important contribution to the design and instrumentation of these experiments.

14. In addition there are a number of programmes with melt simulants. These include molten salt experiments in RASPLAV, the Swiss CORVIS tests, which use an iron-alumina melt interacting with prototypical lower head structures, and thermite spreading tests. Simulant low temperature tests, such as COPO and BALI (both for natural convection, with BALI taking account of gas sparging effects and solidification at the pool boundary) will provide further data for the development and validation of computer models.

15. The attention of CSNI is drawn to the desirability of establishing co-ordination and collaboration between the various experimental programmes.

16. While it was outside the formal scope of this Workshop, it is recommended to prepare a situation report and a Workshop on melt coolability by spreading (as this is an alternative accident management measure proposed to ensure debris coolability following a severe accident) on a time-scale of 2 years.
SESSION I

Title: Feasibility of in-vessel core debris cooling through external cooling of the vesse

Chairman: K. Trambauer (GRS, Germany)

SUMMARY

Session I dealt with different NPP analyses to study the efficiency of in-vessel melt retention through external cooling. It was clearly recognised that this approach requires individual plant examinations, since configuration of RPV and the cavity where it is situated, as well as decay heat density vary for different NPPs.

Sufficient external cooling requires a large water pool around the RPV as free access of water to the cavity as well as unhindered escape of steam from the lower RPV region to the containment. Under these circumstances, the critical heat flux on the RPV outer surface is the limiting factor. It ranges from 0.2 MW/m² at the center of the lower head, up to about 1 MW/m² at the upper end of the lower head and above.

Following assumptions are common in the analyses:

- as upper bound the whole core relocates into the lower plenum
- significant reduction of decay heat due to fission product release (30 - 80%)
- core slump 3 to 10 hours after shut down.

The key parameters for the heat flux to the RPV wall are:

- decay heat density (less or greater than 1 MW/m³)
- molten pool volume to surface ratio
- peaking factor of heat transfer coefficient between lower crust on RPV wall (~ 1.5).

Also the melt composition - Zr content and degree of oxidation - as well as the possible segregation of metallic melt yielding to a separated metallic layer at the top of the melt with high heat conductivity to the RPV wall should be considered.

Thermal insulation or neutron flux shielding can inhibit the external cooling. In the Loviisa NPP those have to be withdrawn into the lower cavity region (AM measures). If thermal insulation is attached to the outer RPV wall, external cooling is not sufficient. If thermal insulation is accidentally separated from the RPV outer wall, the insulation material might blockage the steam escape from the cavity.

Investigations of the stability of the natural convection along the flow path are required. Due to the large time constant of the thermal behaviour of the RPV wall, periodic alternations with frequencies higher than 0.01 Hz do not diminish the heat transfer to the external coolant.

The in-vessel debris cooling through external cooling is feasible for NPPs with low decay heat density and sufficient external natural convection (VVER 440 Loviisa, AP 600).
If the decay heat density is high \((q > 1 \text{ MW/m}^3)\), the efficiency of external cooling is questionable. To explore the margin to vessel failure further investigations are necessary.

Structure mechanics analyses should distinguish between low external heat transfer coefficient \((q > q_{\text{crit}})\) and high external heat transfer coefficient \((q < q_{\text{crit}})\). In case of low external HTC special attention should be given to the internal heat flux distribution and to the plastic instability of the RPV wall.

Melting or eutectic formation at the inner surface of RPV must be considered in this case. Further, if the failure of the RPV cannot be excluded, disadvantages of a wet cavity to the containment integrity have to be evaluated.

The feasibility studies should also include containment bypass sequences and shut down conditions during maintenance.

Briefly, the individual papers focused on the following points:

- The first presentation, authorised by UCSB, IVO and Tenera Staff, discussed two integrated approaches to in-vessel melt retention through external cooling for two different NPP concepts, one -VVER 440 (Lovisa)- in operation since 1978 and the other -AP 600- in design stage. Common to both NPPs are the relative low decay power density \(<1 \text{ MW/m}^3\) and a flooded cavity with high gravity head and sufficient access of water to the RPV. The main differences are the shape of the vessel lower head and the relative height of the molten pool in the RPV.

  Supported by experimental data from COPO (molten pool heat flux distribution) and ULPU (critical heat flux to external coolant) it could be shown, that for both NPPs the local heat flux from the molten pool to the RPV wall stays with a sufficient margin below the local critical heat flux at the vessel outer side. This means, that the high heat transfer coefficient at the RPV outer side keeps the wall temperature low enough with sufficient strength to keep the melt inside the RPV. Under the assumption that a metallic melt layer (thickness about 0.1 m), located on the top of the ceramic melt, directs the heat flow to the RPV, the heat flux distribution did not alter significantly.

- The British presentation (AEAT) highlighted open questions found during the study of in-vessel coolability by ex-vessel flooding for a 1100 MW - 4 loop Westinghouse PWR. Due to higher decay heat density \((> \text{ 1 MW/m}^3)\) local critical heat flux at RPV outer side will be exceeded (3 hours after SCRAM).

  In case of jet attack to the instrumentation penetration, conservative assumptions indicate penetration ejection under high system pressure. To narrow the failure margin more detailed analyses are required. These analyses should consider eutectic formation, concentration profiles in case of conduction limited heat transfer, heat removal by latent heat transport (remelting of freezeed particles), and separation of ceramic and metallic melt layers due to metal segregation.

  Special attention will be given to the effect of in-vessel debris coolability due to in-vessel water addition.

- The French presentation (IPSIN, CEA) discussed the RPV lower head behaviour of a French 900 MW PWR. In case of a large LOCA, dry vessel and dry cavity the RPV will fail in 1 to 2½ hours. Water in the vessel rises the potential not to fail the RPV, especially if the debris size is large enough to enable debris bed coolability. The failure margin for the case dry vessel and wet cavity was investigated by parametric variation of internal heat flux in the range of 200 to
1300 kW/m², internal pressure and external heat transfer coefficient (2 and 10 kW/m²K). Based on the temperature distribution in the vessel wall, the creep failure time was estimated. More detailed calculations to assess the creep failure time in case of externally insulated RPV, under consideration of critical heat flux experiments (SULTAN) and creep rupture experiments (RUPTHER) will be performed. Also advantages and disadvantages (steam explosion) of a wet cavity will be evaluated.

- The first German presentation (KfK) discussed the load-carrying capacity and failure due to plastic instability of a pressurised and externally cooled RPV utilising the ABAQUS finite element code. The temperature depended parameters of the model were fitted by comparison to experimental data up to 900°C.

On a simplified geometry the effect of different external heat transfer coefficients and various wall inner surface temperature on stress-redistribution and plastic instability for a given pressure have been studied.

The model with axisymmetric RPV geometry indicated a critical pressure of 19 MPa for an external heat transfer coefficient of 1000 W/m²K. Comparison to three dimensional RPV geometry with a limited local hot spot indicated that the axisymmetric model yields a lower critical pressure and that the simplified geometry is a lower bound for the load carrying capacity of the RPV.

- The second German presentation (GRS, without paper) which was held instead of the withdrawn paper of SIEMENS, discussed a new attempt to interpret TMI-2 observations. The TMI-2 Vessel Investigation Project resulted in the findings, that outside a hot spot the vessel wall temperature did not exceed 1000 K. Within the hot spot the maximum temperature reached about 1400 K over 30 minutes. Subsequently, a moderate cool down to 1000 K within 15 to 45 minutes occurred. To reconstruct this thermal behaviour, an attempt was made to get insight about the possible heat sink of water penetration in between the lower crust of the melt pool in the lower plenum and the vessel wall. Two dimensional transient heat conduction in the vessel wall, one dimensional steady state heat conduction in the crust, transient lumped parameter approach for the molten pool temperature and one dimensional homogeneous coolant flow in the gap were modelled using the ATHLET code. It could be demonstrated that a coolant flow of 100 g/s can terminate the continuous heat up at the hot spot. Coolant flow of 200 g/s, penetrating one hour after melt slump the gap below the hot spot, yields the moderate cool down starting from the maximum temperature estimated by the metallurgical examinations. Further investigations to explain the quenching process are initiated.
SESSION II

Title: Experiments on molten pool heat transfer

Chairman: J. Bardelay (IPSN)

SUMMARY

The first presentation was performed by M Sonnenkalb of GRS. The title was "Summary of Previous German Research Activities and Status of GRS Program on In-Vessel Molten Pool Behaviour and Ex-Vessel Coolability".

The presentation was divided into two parts:

1. Results of an experimental and theoretical program which was carried out by Pr. Maylinger of Hanover in the years 1970-1982.

   This program was a study of the molten pool behaviour and especially the heat transfer properties from the pool in the upward and downward directions. The experiments were realised in a small scale test facility in a semicircular geometry by using simulant materials for melt.

   The experiments were limited to 2D.

   One conclusion from the first results is that at the lower and upper bounds, a local distribution of Nusselt number exists. The parameters characterising and influencing the convection flow regime were studied: the basic convection flow regime does not change at higher modified Rayleigh numbers greater than the critical Rayleigh number. Some semi empirical equations describing the average Nusselt number were elaborated in two directions on basis of a modified Rayleigh number in the range of $10^7<<5 \times 10^{10}$.

   The free convection heat transfer at lower fluids levels were also studied.

   An important part of the studies concerned a fluid jet flowing from above into the pool. Many sets of experiments were performed with variations of parameters: velocity and width of jet, height of fluid pool, temperature of jet, position of jet. As a result of different analyses some empirical equations were established to describe the heat transfer as a function of $Gr/Re^2$.

2. GRS program on accident management mitigation

   Actual program started in 1993 on the basis of previous programs. The activities are for exemple:

   -- examination of different severe accidents in German PWR and BWR by using codes corresponding to the different accident phases

   -- examination of different accident management procedures:
• to maintain the RPV integrity,
• to maintain the containment integrity,
• to limit F.P. release to the environment.

-- a preliminary situation report on in-vessel phenomena and ex-vessel coolability was realised.

The Germans think that the ex-vessel cooling could be a realistic measure to maintain the molten pool within the vessel under specific boundary conditions. But the most realistic simulation is a big problem.

Dr. Turland (UKAEA) presented the paper entitled "Experiments on convection and solidification in a binary system" prepared with S.B. Schneider.

A series of experiments at Culham Laboratory were undertaken to investigate the modification of the distribution of heat flux to the pool boundary if an hypothetical large molten pool was not a pure material, namely UO$_2$ - ZrO$_2$. The origin of modification may be the precipitation of UO$_2$ rich phase near a cold boundary with the change of stability of the liquid layer, the accumulation of precipitate or remelting of precipitate in hotter region. The experiments were performed in a well insulated tank (200 mm x 200 mm x 104.5 mm) with aqueous salt solutions and employed a cooled top plate and a lower heating plate.

The following sets of experiments have taken place:

• Preliminary series with pure water for comparison with other convection experiments and for being a reference for the salt solution experiments,

• A first series with a binary system used a sodium sulphate solution,

• A final series with a sodium nitrate solution which formed smaller crystals.

The results were:

• Pure water: good agreement for relationship between heat flux and temperature difference for experiments under transient and steady state conditions. It was found possible to correlate Nusselt number and Rayleigh number for Rayleigh numbers greater than 1.5 x $10^9$. The comparison of this model with the correlation of Kulacki and Emara gives a difference of a factor 2.

• Sodium sulphate solution: a stable layer did form beneath the cooling plate due to the salt precipitation. For low Rayleigh numbers, heat transfer coefficients were lower than those determined for pure water, whereas there was no difference at high Rayleigh numbers (turbulent mixing).

• Sodium nitrate solution: the results confirm the previous results but there was some evidence for enhancement of heat transfer due to cycling of precipitate but not at high heating rates.

In conclusion, the transition in behaviour occurred at much lower Rayleigh numbers than expected in a reactor scale melt pool, so these effects are not expected to be important at full scale. But these results must be confirmed with prototypic materials if possible.
M. Kymäläinen presented a paper about "experiments on heat flux distribution from a large volumetrically heated pool".

The study is motivated by an interest in arresting the progression of a hypothetical severe accident in the reactor vessel by flooding the reactor cavity. For keeping the pool inside the vessel it must be shown that nowhere the heat flux is high enough to cause significant local wall thinning and that everywhere the local fluxes are below the local critical heat flux limits on the outside. The study was performed for Loviisa plant which have a dished shape lower head, a pool which extends into the cylindrical portion of the vessel and a maximum pool height of 1.2 m which corresponds to a modified Rayleigh number of $\sim 3 \times 10^{14}$. The experimental facility was COPO which is a 1/2 scale model of lower head of Loviisa RPV (2- dimensional slice). The fluid is a conducting $\text{ZnSO}_4 - \text{H}_2\text{O}$ solution.

The interpretation of the results shows:

- **Average heat fluxes:**
  For the upward heat fluxes, it can be observed a deviation ($<30\%$) between the experimental data and the correlation of Steinbemer and Reineke for $\text{Ra} > 5 \times 10^{14}$; with lower Ra agreement is good. On the vertical boundary there is a good agreement. For the downward heat flux, the agreement is seen good with the Mayinger correlation. It depends on position along the curved wall.

- **Heat flux distributions:**
  For horizontal heat fluxes, there is no systematic tendency for peaking in the upper portion of pool boundary.

The title of the last paper was "SCARABEE BF1 experiment with a molten $\text{UO}_2$ pool and its interpretation". It was presented by M. Kayser from CEA.

The aim of the experiments was to study the natural convection heat transfer in the pool in the frame of fast reactor safety analysis. The test was performed in 1985 with 5 kg molten $\text{UO}_2$ in a 6 cm diameter stainless steel crucible cooled by flowing sodium. Different tests were performed with specific powers up to 140 W/cm$^3$. Ultrasonic thermometers measured the pool temperature up to $3000^\circ\text{C}$.

The results were analysed by the THEBES code, by Seiler's correlations established through the BAFOND water tests and by Kulacki and Emara's correlation for axial heat transfer. It has been established that a fuel crust building up or remaining on the wall is a very effective protective layer. The crust has resisted to fluxes up to 200 W/cm$^2$. The study of convective heat transfer was performed but due to the experimental difficulties in measuring high temperatures the numerical interpretations are not very precise. Some other interpretations were interesting:

- The top heat removal through radiation was $\sim 25\%$ of total power

- The experimental heat transfer to the top was higher than the prediction (factor of 4). This could be due to a phase change at the surface (solidification and subduction)

- The application of Seiler's correlation for radial heat transfer gives too small heat transfer coefficients. The difference could be explained by uncertainties on physical properties.

- Despite the uncertainties, for many applications in safety these correlations may give a sufficient estimation of an order of magnitude.
SESSION III

Title: Calculational Efforts on Molten Pool Convection

Chairman: B.D. Turland (AEA Technology)

SUMMARY

- M. Dhir (UCLA) described experiments on natural convection heat transfer in volumetrically heated spherical pools. The liquid was Freon 113, contained in a pyrex belljar, heated by microwaves and cooled by a surrounding water pool. Calibration runs indicated that this system provided a good simulation of volumetric heat generation. Three different diameters were used: 152 mm, 210 mm and 440 mm. Fill ratios for the hemisphere (H/R) were varied from 0.26 to 1.0; most experiments had a free top surface, but some used a rigid lid with and without cooling. The data were well-correlated by a Nu-Ra numbers relationship similar to that obtained by Mayinger.

Data and correlations for the dependence of heat transfer on position around the downward facing surface were given; the peak heat flux was found to be 2-2.5 times the average.

- M. Pigny (CEA-Grenoble) presented a preliminary study of flow and heat transfer in a corium molten pool in a reactor lower head and in an ex-vessel core catcher. Calculations were performed with the TRIO-VF code, which includes a k - ε, model for turbulent flow. Rather than attempt to resolve the thermal boundary layers in detail, a local heat exchange was used. Heat transfer in the walls and wall melting were considered. For the lower head calculation only 21% of the heat was radiated from the top surface (low emissivity of the surrounding steel) and the maximum heat flux to the wall is 1.3 MW/m². Unless nucleate boiling is assumed this leads to wall failure by melting. The ex-vessel calculation assumed a separated vapor layer, and rapid failure of the container was calculated.

- M. Dinh (Electrogorsk) described calculations for the COPO experiments with the NARAL code, which uses a 2-D co-ordinate transformation technique and the low Reynolds number turbulence model of Chien.

Dinh argued that a Reynolds stress model may be needed, but it was worth considering whether acceptable results could be obtained using a modified k - ε model. Using the unmodified Chien model, the upward heat was underestimated by a factor of about 2.5, whilst the lateral heat flux was overestimated by a small amount.

Grid refinement studies indicated that a converged solution had been obtained. Modifications were introduced to the wall convection for the turbulent viscosity coefficient and to the turbulent Prandtl number based on the local Richardson number (ratio of buoyant to shear turbulent production). With these modified functions the overall heat transfer characteristics of the COPO tests could be reproduced.

- M. Strizhov (Russian Academy of Science) also presented calculations for COPO using a code (RASPLAV) with a k - ε turbulence model; an analytical turbulence model was also used. The model has been validated using data from a number of experiments, including experiments with volumetric heating and isothermal walls. For the high Rayleigh numbers in the COPO experiments, a strong mesh dependency on the calculated upward heat flux was found: for convergence a sub-millimetre grid at the top surface is required.

Simulations were also presented for the RASPLAV facility, coupling an internal flow, heating and melting of the vessel and external heat removal by convection.
Status of computational modelling

In principle, computational models based on CFD (Computational Fluid Dynamics) are desirable for molten pool heat transfer. The benefits include interpretation of the existing data base, the possibility of limited extrapolation in Rayleigh number and geometry, and the inclusion of effects which are difficult to achieve in simulant tests (e.g. radiative effects, stratified oxidic/metallic layers).

The first object of the work is to establish a capability that is economic and can reproduce the existing experimental data base. While work presented at the meeting and elsewhere has demonstrated significant progress towards achieving this objective, the difficulty is that there is no agreed model for turbulent heat transfer under strongly buoyant conditions. In the papers presented the authors took three different approaches:

1 - Do not attempt to calculate the boundary layers. Use the standard k - ε for the bulk and a local correlation for heat transfer at the wall.

2 - Modify a low Reynolds number k - ε model by making the turbulent Prandtl number and wall functions depend on the local stratification conditions.

3 - Use standard k - ε model or analytical turbulence models with minimal changes to obtain reasonable agreement with the experimental data in the turbulent regime.

Approaches 2 and 3 both compared reasonably well with COPO data - some difference in convergence properties were noted, and it may be concluded that tests with a fine mesh close to the surface should be done to ensure convergence. However the work of Strizhov shows that these calculations do not have to be particularly computer-intensive.

In practical applications the need for detailed calculations depends on the likely margin. If this is high, relatively conservative assumptions (e.g. on peaking ratio) of the heat flux are likely to be acceptable - and as easy to defend as the details of any particular turbulence model. If the margin is non-existent, calculations will not help. This probably leaves a relatively narrow band of low margin where detailed calculations would support a safety case; this implies that the models should have a high degree of validation and robustness.

Recommendations for future work

(1) Based on the understanding of experimental data and the detailed simulations, consider the development of a simplified practical pool model

(2) Effort now needs to be placed on validating the CFD models for low Prandtl number materials, for application to steel layers

(3) Consideration needs to be given to other processes that might modify the heat transfer in the reactor application such as freezing from multi-component systems at interfaces.
SESSION IV

Title: Heat Transfer to the Surrounding Water - Experimental Techniques

Chairman: H. Tuomisto (IVO, Finland)

SUMMARY

A basic element of the in-vessel retention of corium is to ensure sufficient heat transfer from the submerged reactor vessel to the surrounding water. Obviously, the only way is to maintain nucleate boiling regime on the vessel outer surface. The conditions of maintaining nucleate boiling are that

- the vessel is submerged deeply to the water and an effective water circulation can be sustained, and that
- the critical heat flux i.e. long-term film boiling conditions can be avoided.

The vessel submergence requires that there is enough water available inherently or through efficient accident management measures to flood the vessel up to the vessel supports. Additionally, a free flow path has to be ensured to form a free circulation loop with a downcomer section back to the cavity. It has to be checked that the thermal insulation of the vessel or loose insulation debris cannot clog these flow paths. The flow instabilities of the circulation loop have to be accounted for.

The critical heat flux (CHF) studies involve several aspects. The boundary conditions come from the heat transfer distribution inside the vessel. Most limiting conditions are those of the convective corium pool. The CHF considerations outside the vessel are characterised by

- large flow channels
- thick heater walls i.e. the vessel wall having a very large thermal inertia
- downward facing, curved surfaces
- vertical vessel surface in some cases
- annulus geometry
- subcooling due to hydraulic head
- surface wetting properties.

- The first paper of Session IV by CEN-Grenoble presented the draft of the report prepared for CSNI/PWG4 on "Core Debris Cooling with Flooded Vessel or Core-Catcher Heat Exchange Coefficients under Natural Convection". The purpose of this report is to summarise state-of-art of the vessel outside cooling concentrating on the above mentioned aspects.

- The second paper by Sandia National Laboratory and USDOE gives the results of the first experiments from the CYBL facility. These full-scale tests demonstrated that the nucleate boiling conditions on the surface of the fully submerged torospherical lower head can be maintained for heat fluxes up to 200 kW/m².

- The third paper by UCSB and IVO International supported by USDOE presented the results of the full-scale CHF studies through the curved, downward facing thick walls in the ULPU-2000 facility. The results indicate that the CHF lower bound of downward facing curved surface is about 300 kW/m². When taking into account the heat flux distribution from the molten pool, it seems evident that the limiting conditions of CHF do not take place in the downward facing part of the lower head but near the upper part of hemispherical bottom approaching to vertical vessel wall.
The fourth paper by CEA-Cadarache concentrated on the TRIO-VF calculations of the behaviour of a corium pool and TRIO-GENEPI calculations of the vessel external cooling for a future PWR. The preliminary results emphasised the need for further development in calculation methods to achieve realistic modelling of the in-vessel retention concept.

The general conclusions of Session IV are that the flow paths and the vessel submergence require case-by-case very plant-specific evaluations. The available ULPU-2000 and CYBL results show that the CHF values of downward facing surfaces are clearly higher than corresponding downward heat fluxes from the corium pool. The limiting heat flux situations arise when approaching to the vertical sections of the vessel lower head.
SESSION V

Title: Future Experiments and Ex-Vessel Studies (open forum discussion)

Chairman: B. Kuczera (KfK, Germany)

SUMMARY

The session was composed of seven contributions which gave a perspective on future experimental activities rather than on current experimental results. Its sequence was as follows:

- First, Mr. V. Strizhov (Inst. of Nuclear Safety, Russian Academy of Sciences) presented a profound overview on the OECD Project RASPLAV. The purpose of this international project is the performance of integral in-vessel melt pool experiments with prototypical core material compositions and core melt temperatures. This main part is accompanied by separate effects test which should provide the necessary data base on relevant corium material properties and by a broad model development program which may allow to transfer experimental findings on real reactor conditions. The main test program is split up into two parts:
  - One part will be conducted in the RASPLAV facility which represents the 2D slice geometry of a VVER lower vessel head;
  - The second part will be performed in 3D hemispherical or elliptical lower vessel head geometry.

Both facilities allow to treat with up to 200 kg Uranium melt; the decay heat release is simulated by corium heat through the graphite side walls (A) and by direct current heating (B), respectively. Heat removal from the melt region will be realised by molten salt cooling of the vessel wall. The extensive separate effects tests program will be performed in various facilities already available. Current model developments both in 2D and 3D geometry is supposed to support this ambitious program in the most efficient way.

- Model development was also the subject treated in the second paper. Mr. B. Spindler (CEA, France) reported on the French code TOLBIAC which will be applied for the simulation of the thermohydraulic behaviour of a molten core with simultaneous wall ablation. The model is based on a 3D concept and treats three components: a metal liquid phase, an oxide liquid phase and a gas phase for the representation of the ablation products like carbon dioxide and vapour. Two versions will be provided, one is oriented on the corium behaviour in the lower vessel head, the other on corium behaviour in a core catcher. First results from a simplified code version have illustrated preliminary results of both code versions. In this context the need of appropriate material properties was again emphasized.

- The third contribution was entitled “Feasibility of an experimental program on the corium retention issue for ALWR plants”. In the first part, Mr. F. ParoZZi (ENEL, Italy) illustrated the current capabilities of the CORIUM-2D model with regard to in-vessel and ex-vessel corium behaviour; the second part presented by Mr. D. Magallon (JRC Ispra, CEC) summarised how the corium retention issue could be addressed experimentally in FARO as part of the fourth framework program (1995-98) of the CEC. For this purpose the FARO facility could be modified which then would allow to handle corium melt masses up to 350 kg. In this context external water cooling and flooding of the melt debris is taken into consideration. An indicative test matrix of eight corium cooling and retention experiments has been proposed.
• In the fourth presentation Mr. J.M. Seiler (CEA, France) illustrated the large scale projects BALI and SULTAN devoted to core melt retention investigations. While the BALI project is more oriented to large molten pool heat transfer phenomena in a hemi-cylindric scale geometry, concentrates the SULTAN project more on ex-vessel or core-catcher boiling phenomena. The test section represents a rectangular 4 m long channel which can be fixed in various inclined positions. Both projects will extend the data base which is used for the validation of the TOLBIAC code.

• A status report on the Swiss CORVIS Project was presented by Mr H.M. Kottowski (PSI, Switzerland). In the CORVIS experiments, the behaviour of a molten corium pool in the lower vessel plenum is simulated. The corium is represented either by up to 1000 kg oxide melt or 1000 kg metal melt generated by a preceding thermite reaction; a special DC arc heating device simulates decay heat generation. The test CORVIS 02/1 recently carried out was chosen, as an example for illustration. In this experiment a jet impingement of the melt caused an unexpected failure of the sidewall of the crucible and major portions of the melt were poured into the vicinity. Current post-test analyses lead to an improved understanding of the complex material interaction processes. At the same time the CORVIS project serves as an attractive nucleus for a broad international collaboration.

• A further ambitions, large scale UO\textsubscript{2} program on corium behaviour and cooling for future LWRs was presented by G. Cognet (CEA, France). The VULCANO Project is focused on key phenomena involved in the behaviour of corium and its cooling possibilities under both, in-vessel and ex-vessel conditions. There are two project phases: VULCANO-E-30 will be performed with corium masses between 30 and 100 kg in order to get the basic knowledge; for the second phase VULCANO-E-500, where the corium mass will be increased to 500 kg and above. Current investigations concentrate on a new plasma technique for corium melting and on a refinement of the test instrumentation as well as on the corium sustained heating technique. The test matrix of E-500 will be defined in more detail on the basis of experiences gained in E-30.

• Finally, an ad-hoc presentation on the French CORINE program was given by Mr J.M. Veteau (CEA, France). In the current melt spread investigation program low melting point simulant materials are used in order to extend the basic knowledge of relevant processes. In so-called type-1 tests water-glycerol mixtures may provide some generic information, which will be re-checked in type-2 tests to be performed with Bi-Sn alloys. The spreading area is represented by a planar 19° angular sector with a radius of 6.5 m. In subsequent, type-3 experiments the crust formation kinetics and the ablation velocity of the bottom material are in the baseland of the investigations.

Concluding remarks drawn from Session V:

The outlined future R&D activities on molten pool behaviour will support an improved understanding of the complex severe accident phenomena and, thus, support the innovative trend towards an enhancement safety quality of future LWRs. The R&D work comprises ambitious projects the generic and design specific results of which will probably not meet all present objectives. However, the investigations will provide essential information which will contribute to the validation of the defence-in-depth strategy from deterministic point of view. In any case, the activities will stimulate an intensification of international collaboration in the nuclear safety area.
APPENDIX

MEMBERS OF THE PROGRAMME COMMITTEE

Mr. Joël Bardelay (IPSN, France)
Dr. Sudhamay Basu (USNRC) (unable to attend the meeting)
Prof. Dr. Helmut Karwat (TUM, Germany) [replaced at the meeting by
Dr. Klaus Trambauer (GRS, Germany)]
Dr. Ing. Bernhard Kuczera (KfK, Germany)
Dr. Harri Tuomisto (IVO, Finland)
Mr. Jean-Marie Seiler (CEA, France)
Dr. Brian D. Turland (AEA Technology, UK)
Dr. Jacques Royen (OECD/NEA) (Secretary)