

Unclassified

NEA/CSNI/R(98)18



Organisation de Coopération et de Développement Economiques
Organisation for Economic Co-operation and Development

OLIS : 22-Feb-1999
Dist. : 25-Feb-1999

English text only

**NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS**

**NEA/CSNI/R(98)18
Unclassified**

**IN-VESSEL CORE DEBRIS
RETENTION AND COOLABILITY**

Workshop Proceedings

**3-6 March 1998
Garching near Munich, Germany**

74703

**Document incomplet sur OLIS
Incomplete document on OLIS**

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- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

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The primary objective of the NEA is 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.

This is achieved by:

- *encouraging harmonization of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;*
- *assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;*
- *developing exchanges of scientific and technical information particularly through participation in common services;*
- *setting up international research and development programmes and joint undertakings.*

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

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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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 co-ordinate the activities of the 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.

CSNI constitutes a forum for the exchange of technical information and for collaboration between organisations which can contribute, from their respective backgrounds in research, development, engineering or regulation, to these activities and to the definition of its programme of work. It also reviews the state of knowledge on selected topics of nuclear safety technology and safety assessment, including operating experience. It initiates and conducts programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach international consensus in different projects and International Standard Problems, and assists in the feedback of the results to participating organisations. Full use is also made of traditional methods of co-operation, such as information exchanges, establishment of working groups and organisation of conferences and specialist meetings.

The greater part of CSNI's current programme of work is concerned with safety technology of water reactors. The principal areas covered are operating experience and the human factor, reactor coolant system behaviour, various aspects of reactor component integrity, the phenomenology of radioactive releases in reactor accidents and their confinement, containment performance, risk assessment and severe accidents. The Committee also studies the safety of the fuel cycle, conducts periodic surveys of reactor safety research programmes and operates an international mechanism for exchanging reports on nuclear power plant incidents.

In implementing its programme, CSNI establishes co-operative mechanisms with NEA's Committee on Nuclear Regulatory Activities (CNRA), responsible for the activities of the Agency concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with NEA's Committee on Radiation Protection and Public Health and NEA's Radioactive Waste Management Committee on matters of common interest.

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B SUMMARY AND CONCLUSIONS

1. Introduction

1.1 Sponsorship

The CSNI Workshop on In-Vessel Core Debris Retention and Coolability, held on 3rd-5th March 1998 in Garching near Munich, Germany, was sponsored by the Committee on the safety of Nuclear Installations (CSNI) of the OECD Nuclear Energy Agency (NEA). It was organised in collaboration with Gesellschaft fuer Anlagen- und Reaktorsicherheit (GRS) and the Technical University of Munich, Institute A for Thermodynamics.

1.2 Background and Objectives

In the spring of 1994 an OECD Workshop on Large Pool Heat transfer was held in Grenoble. The scope of this workshop was the investigation of (1) molten pool heat transfer, (2) heat transfer to the surrounding water, and (3) the feasibility of in-vessel core debris cooling through external cooling of the vessel. Since this time, experimental test series have been completed (e.g., COPO, ULPU, CORVIS) and new experimental programs (e.g., BALI, SONATA, RASPLAV, debris and gap heat transfer) have been established to consolidate and expand the data base for further model development and to improve the understanding of in-vessel debris retention and coolability in a nuclear power plant.

Discussions within the CSNI's PWG-2 and the Task Group on Degraded Core Cooling (TG-DCC) have led to the conclusion that the time was ripe for organizing a new international Workshop with the objectives

- to review the results of experimental research that has been conducted in this area
- to exchange information on the results of member countries experiments and model development on in-vessel core debris retention and coolability.
- to discuss areas where additional experimental research is needed in order to provide an adequate data base for analytical model development for core debris retention and coolability.

The scope of this workshop was limited to the phenomena connected to in-vessel core debris retention and coolability and did not include steam explosion and fission product issues.

The workshop was structured into the following sessions

1. Key note papers
2. Experiments and model development
 - 2.1 Debris bed heat transfer
 - 2.2 Corium properties, molten pool convection and crust formation
 - 2.3 Gap formation and gap cooling
 - 2.4 Creep behaviour of reactor pressure vessel lower head

- 2.5 Ex-vessel boiling and critical heat flux phenomena
- 3. Scaling to reactor severe accident conditions and reactor applications

The program committee, nominated by the TG-DCC and approved by PWG2, was:

Dr. Ali-Reza Behbahani, USNRC
Mr. Andrzej Drozd, NEA (secretary)
Dr. Sang-Baek Kim, KAERI, Korea
Dr. Jean-Claude Micaelli, IPSN, France
Dr. Timo Okkonen, ABB, Sweden
Dr. Jun Sugimoto, JAERI, Japan
Dr. Klaus Trambauer, GRS, Germany (chairman)
Dr. Harri Tuomisto, IVO, Finland

The meeting was attended by 91 participants from 15 OECD countries and one non-OECD country: Germany (28), France (22), Finland (7), USA (6), Italy and Sweden (5 each), Russia (4), Japan (3), Belgium, Czech Republic and Hungary (2 each), Austria, Korea, Netherlands, Switzerland and UK (1 each).

2. General remarks and Conclusions

2.1 General Conclusions

Compared to the previous workshop held in Grenoble in 1994, large progress has been made in the understanding and the modelling of several phenomena involved in the domain of interest. They concern :

- the corium properties
- the molten pool convection
- the gap formation and cooling
- the creep behaviour of the lower head
- the ex-vessel critical heat flux

and they are discussed in the session specific conclusions (chapter 2.2).

Some conclusions have been reached and some outstanding questions have been identified during the general discussion :

- Plant specific studies performed on core melt retention indicate with high confidence level that the in-vessel retention concept is possible for low ($\sim 600 \text{ MW}_{el}$) power reactors.
- Convective corium pool behaviour with all chemical and physical aspects requires still confirmatory research. Such as being carried out in OECD Rasplav project. The pool formation and the initial conditions in the lower plenum are plant and accident sequence dependent and are subject to large uncertainties.
- Since in-vessel coolability cannot be ensured (e.g., for high power plants), it is highly desirable to understand RPV lower head mechanical behaviour (i.e., size, location and time to failure) and to improve the modeling of creep rupture behaviour.
- For severe accident analyses different approaches are useful :
 - Obtain physical understanding by well designed experiments and detailed code calculations
 - Apply integral codes to obtain scenario and system effects such as timing
 - Complement remaining shortcomings by separate engineering calculations when necessary
- One of the most important work is to develop a consistent severe accident management strategy for each individual plant. This ensures the above discussed chemical and physical phenomena do not cause confusion among the reactor safety society.

2.2 Session specific conclusions

2.2.1 Debris bed heat transfer

Progress in understanding and modelling is underway, however no new result impacted the feasibility of the In Vessel Retention concepts.

No priority needs have been identified, nevertheless efforts should be maintained to enrich the knowledge of basic phenomena involved in severe accidents, and increase the capability of numerical tools to predict scenarios.

- ◆ Compared to the results of the previous workshop, it can be recognised that the scope of the analytical tools has been enlarged to consider the heat transfer to two-phase water flow. The debris formation was not covered in the previous workshop; the FARO facility provided quantitative results, but up to now there are difficulties to transpose them to reactor scale.

2.2.2 Corium properties, molten pool convection and crust formation

Some corium properties have been measured in RASPLAV project as presented in one of key note papers, and physico-chemistry and corium properties have been discussed. Although new findings are being obtained, a wide variety of property measurements and analysis will be needed.

The effect of mushy zone on the heat transfer could be important and should be clarified.

Concerning molten pool natural convection and crust formation, extensive experimental and analytical studies are being conducted. More careful attention should be paid for synthesising the results of several different experiments. Also emphasise should be paid on the physical and chemical mechanism, such as non-eutectic mixtures and phase segregation, as well as for the model development and code assessment. The relevance of enhanced natural convection due to boiling processes with bubble formation has not been verified yet.

- ◆ The chemo-physical behaviour of the corium melt, the melt segregation and the formation of a metal-rich layer on the top of the ceramic melt pool were discussed already in the previous workshop. The data base for these phenomena has been significantly enlarged, but confirmatory research is still needed, especially for the corium properties and the transposition of simulant test results to the reactor problem.

2.2.3 Gap formation and gap cooling

The formation of gaps with a width in the order of a couple of mm has been confirmed after relocation of corium melt masses up to 200 kg in ALPHA, LAVA, FAI and FARO experiments.

The total power transfer to the fluid in narrow gaps is limited by dry-out rather than critical heat flux.

The measured maximum heat flux (100 to 500 kW/m²) which results in gap dry-out increases with gap width, pressure and sub-cooling. At higher heat flux longer local dry-out periods result in wall temperatures higher than Leidenfrost temperature and spontaneous re-wetting is not possible.

Discrepancies regarding the dependency of maximum heat flux on pressure between different test facilities should be investigated.

Internal gap cooling requires long-term availability of water and stable crust formation. The latter is questionable for larger melt pools and for metal rich-melts. The tendency of better cooling conditions at higher pressure due to gap formation and higher heat flux is contrary to

depressurisation as severe accident measures. Its safety relevance was questioned, nevertheless internal gap cooling seems to be important for specific sequences, as seen in TMI-2

- ◆ In the previous workshop this phenomenon was not covered, except in one presentation (not included in the proceedings) where this was discussed as a possible explanation for the cooling of the hot-spot in the TMI-2 accident, which was found in the TMI-VIP. Since then, extensive progress has been achieved in understanding gap formation and gap cooling behaviours. This confirms that this phenomenon is a possible explanation of cooling of the hot spot of TMI-2, nevertheless the formation and stabilisation conditions are not enough understood for a practical applications to the reactor.

2.2.4 Creep behaviour of reactor pressure vessel lower head

Further knowledge of the RPV lower head material properties are needed for adequate modeling of strain and stress behaviour.

Additional integral RPV lower head structural integrity experiments scaled properly for wall thickness need to be carried out.

Further experimental study on the RPV lower head creep behaviour needs to be performed at lower pressures.

- ◆ In the previous workshop there was presented only one structural analysis of the failure of RPV wall due to thermal and mechanical loads. Now the experimental data base is considerably enlarged with physically based thermal boundary conditions.

2.2.5 Ex-vessel boiling and critical heat flux phenomena

The experiments confirmed high heat transfer coefficients for ex-vessel boiling.

The plant specific design of RPV, cavity and insulation structure have important impact to the maximum heat transfer to the external coolant. The gravity driven flow is sensitive to steam venting.

Feasibility studies of ex-vessel cooling must consider the effect of reduced heat transfer due to degradation of insulation, unavailability of flow paths, etc.

- ◆ In the previous workshop this phenomenon was covered by one session, presenting data from two experimental facilities and planned investigations. The data base is now considerably enlarged and the cooling process is quite well understood.

2.2.6 Scaling to reactor severe accident conditions and reactor applications

The results and the extensive expert review process of the AP-600 in-vessel retention study have been presented and discussed.

The reasonability of applying integrated severe accident codes for physical studies have been demonstrated. It was recognised that integrated codes are sometimes applied outside their original scope and that the practical assessments and decisions concerning severe accident management require sound physical understanding of the phenomena that can be obtained through separate effect experiments and analytical work.

- ◆ Compared to the previous workshop the analytical tools have been improved. The employed models have still some uncertainties e.g. with respect to accident scenario dependency. These uncertainties can be evaluated by varying sensitive parameters.

2.3 Questions and Answers

According to the announcement of the workshop the following questions were discussed:

- Are there accident management measures which significantly delay RPV failure due to the thermal and mechanical loads of the core debris?

Answer:

There is no change in the strategy to bring in water into the primary system as soon as it is feasible.

- What can we do for existing LWRs to retain core debris in vessel?

Answer:

The answer is very plant specific. In-vessel melt retention depends on power level, geometrical features and the availability of water. If the cavity is to be flooded, one should show the sufficiency of cooling for all pertinent scenarios or, when this fails, study carefully the consequences in case of vessel failure.

- How to retain the core debris in the vessel of future reactor designs without external flooding?

Answer:

The only way is to get sufficiently early long-term availability of water, and to bring it in the vessel in order to prevent core debris relocation into the lower plenum. For sequences significantly delayed with water availability, internal core catchers have been proposed, but up to now they do not guarantee efficient corium cooling.

- What is the upper limit of thermal power which guarantees the core debris retention in the RPV?

Answer:

In general terms the thermal power depends on nominal power, accident sequence, size of vessel, corium composition, ex-vessel conditions and the necessary failure safety margin.

- What are the additional needs for experiments, model development, and code development?

Answer:

Besides the needs formulated in the general discussion above, research on national level is determined by specific requirements which consider verification or confirmation of physical and chemical models, the validation of computer codes as well as the maintenance of knowledge and the qualification of experienced staff in nuclear reactor safety.

3. Summary of presented papers and session specific conclusions

3.1 Key note papers

Prof. Unger gave a presentation on various aspects of the use of nuclear power and the use of energy world-wide. After that he focused on key phenomena of late-phase melt progression and their relationship to severe accident management and code modelling. Also the key issues of early-phase core degradation were covered. From the accident management point of view, the main questions are the availability and efficiency of water injection into the vessel before the potential for a vessel failure, as well as the feasibility of external vessel cooling to prevent a vessel failure even with a complete core meltdown. There are uncertainties associated with some of the key phenomena, and their modelling in codes is somewhat different. The implementation of severe accident management requires plant-specific studies and clear operator instructions.

Prof. Theofanous gave a presentation on the in-vessel melt retention as a severe accident management strategy, with a particular focus on external vessel cooling. Design-specific assessments, including detailed phenomenological studies, have been performed for the Loviisa plant and the AP-600 design. The assessments have been subjected to extensive expert reviews and also regulatory reviews. He made the conclusion that the above assessments are well based on both fundamental and practical considerations, and that the strategy is proven for the above low power reactor designs. Closer examinations is necessary for large-power reactors as well as the potential applications for ex-vessel (core catcher) situations. The assessments need to be systematic and transparent, and they need to cover both thermal aspects and potential steam explosion loadings against the vessel lower head. Thermal studies are getting to become fairly mature, while the steam explosion analyses require (and have already stimulated) special modelling advancement. Real-material tests, such as those of the OECD Rasplav project, are important in the sense that they provide generically applicable information about the core melt behaviour and properties.

Dr. Seiler gave a presentation on the GAREC research programme that is being carried out to understand the key processes that would affect the in-vessel melt retention, in particular for large-power reactor designs. The presentation covered the scenarios and the phenomena that are involved during the time frame from core meltdown to melt attack against the vessel. Several questions of importance have been studied and their influence can now be estimated, mostly in a way that favours in-vessel melt retention. Some special issues such as the barium release from the melt pool, as well as their potential influence on decay power generation and thermal margins, need to be further investigated. In general, the margins for vessel failure are lower in a large-power reactor and therefore further research is necessary. The main open questions are the focusing effect (metallic layer heat flux) and the fuel-coolant interactions (in case of late water injection), as well as some reactor-specific questions about the core melt relocation process and the subsequent melt attacks and the initial debris configuration in the vessel lower head.

Dr. Asmolov gave a presentation on the progress and the latest findings of the OECD Rasplav project. A large number of experiments have been performed, including both simulant and real-material tests. Data has been obtained for the properties of various core melt compositions and the behaviour of prototypic core melt in a relatively large-scale melting facility. The latest finding is the stratification or segregation behaviour that has been observed for a mixture of UO_2 , ZrO_2 , and Zr. Phase 2 of the OECD Rasplav project is underway.

3.2 Experiments and model development

3.2.1 Debris bed heat transfer

The understanding of phenomena involved in debris bed is important since debris beds constitute the most probable initial condition for corium molten pool formation in the lower head of a RPV. The main questions addressed are the debris bed formation, its coolability (remelting, steam production, drying of lower head), its transition to a molten pool (time and temperature), and the molten pool configuration (stratification)

Five papers were presented in this session, two experimental programmes, two modelling programmes and one uncertainty study:

Magallon made a presentation of FARO results. The formation and the cooling of corium debris beds resulting from corium melt jet quenching tests have been investigated. The influence of several parameters has been analysed (such as pressure, water height, corium mass). The interpretation and transposition to the reactor remain to be done.

Horner presented a more analytical programme dealing with thermal hydraulics and heat transfers in a internally heated debris bed with the evidence of multi-dimensional effects.

Buck presented the WABE-2D and MESOCO-2D codes to be coupled with ATHLET-CD. They treat the two phase flow in the debris bed, and the melting and relocation process within the debris bed respectively.

Fichot presented ICARE2 code and more precisely the melting and relocation module, a reactor application has been discussed

Schaaf presented an uncertainty and sensitivity analysis made with AIDA code. He demonstrated the interest of such a probabilistic approach for the identification of sensitive processes to be modelled, regarding the lower head thermal ablation.

During the concluding discussion of the session, the following main points were raised :

- Progress in understanding and modelling is underway, however no new result impacted the feasibility of the In Vessel Retention concepts yet.
- No priority needs have been identified, nevertheless efforts should be maintained to enrich the knowledge of basic phenomena involved in severe accidents, and increase the capability of numerical tools to predict scenarios.

3.2.2 Corium properties, molten pool convection and crust formation

The objective of this session was to review the corium properties, and to understand the molten pool natural convection and crust formation behaviours in the RPV lower head.

Eight papers were presented in this session, one for corium properties, two experimental and the remaining five analytical works.

The paper presented by Froment and Gueneau deals with physics - chemistry and corium properties that may have consequences on In-Vessel retention capabilities. The separation into two layers (as observed in Rasplav) may be either due to a miscibility gap, or due to some other mechanism (density separation). If the metallic part relocates in the upper part of molten pool, this is expected to decrease the focusing effect, if not more than 50 % zirconium has been oxidised. Significant barium release observed in VERCORS experiments may have influence on the reduced residual power in corium pool. Complementary further investigations are found to be necessary.

Existence of a mushy zone was discussed by Seiler. Using a theoretical formulation with assumptions, a mushy zone cannot exist in thermal-hydraulic steady state condition, as a conclusion. The validity of the assumptions was discussed and further investigation will be continued.

The paper presented by Helle reported results from COPO II-Lo and COPO II-AP experiments with homogeneous pool. The heat transfer coefficients obtained are higher than those in the earlier experiments such as Steinberner and Reineke, COPO I and ACOPO. Several possible reasons for this discrepancy have been investigated.

The paper presented by Bonnet and Spindler deals with BALI experiments for thermal-hydraulic behaviour of molten pool and its numerical simulation with TOLBIAC code. BALI experiments with full scale 2D capabilities showed good agreement with COPO II experiment. For shallow metallic layer, a separate effect experiment showed that a radial temperature gradient in the fluid layer reduces the focusing effect. This reduction is however weak (about 20 % reduction of heat flux on the wall for a 5 cm thick layer).

The paper presented by De Cecco reports TOLBIAC code simulation being pursued for molten salt Rasplav experiments. Further code assessment is ongoing for better agreement between calculations and experimental data.

The paper presented by Dinh reports the first SIMECO experimental results on in-vessel melt pool formation and on heat transfer with and without metallic layer. In a slice-type geometry with a semicircular section and a vertical section, water and eutectic salt as melt simulants were employed. the MVITA code has been applied for pre-test and post-test analysis.

The paper presented by Nourgaliev deals with numerical investigation of turbulent natural convection in an internally-heated melt pool and metallic layer. Turbulent models have been studied and Direct Numerical Simulation method was applied. It was demonstrated that one-point closure turbulence models are unable to describe natural convection flows and heat transfer in unstable / stable-stratified fluid. Future works will focus on the development and validation of Large-Eddy Simulation (LES) approach.

The paper presented by Chudanov reports the current status and validation of CONV2D & 3D code for the analysis of convection / diffusion processes accounting for melting in a wide range of geometric parameters and boundary conditions for laminar, transitional and turbulent regimes. Extensive validation activities such as for Rasplav and ACOPO experiments, have been conducted.

The paper presented by Kondratenko deals with the heat transfer similarity between three-dimensional volume and quasi-two-dimensional analogy employed in simulant experiments in a thin slice geometry. It confirmed the proper design of the employed test facilities.

During the concluding discussion of the session, the following main points were raised :

- Some corium properties have been measured in RASPLAV project as presented in one of key note papers, and physico-chemistry and corium properties have been discussed. Although new findings are being obtained, a wide variety of property measurements and analysis will be needed.
- The effect of mushy zone on the heat transfer could be important and should be clarified.
- Concerning molten pool natural convection and crust formation, extensive experimental and analytical studies are being conducted. More careful attention should be paid for synthesising the results of several different experiments. Also emphasise should be paid on the physical and chemical mechanisms, such as non-eutectic mixtures and phase segregation, as well as for the model development and code assessment. The relevance of enhanced natural convection due to boiling processes with bubble formation has not been verified yet.

3.2.3 Gap formation and gap cooling

The objectives of this session was to investigate the processes of gap formation between core debris and the lower head wall as well as the hydrodynamics of the gap flow and limitations of heat transfer to the fluid.

Six paper were presented in this session, two on gap formation, three on gap thermal hydraulics and one on a planned integral test facility.

The paper presented by Maruyama deals with the fragmentation and quenching of 30 to 50 kg Al_2O_3 in water under 1.3 MPa ambient pressure as well as numerical analysis with CAMP code. The debris behaviour is similar to that observed in FARO test facility with particle and cake formation. There is no sticking of the cake with the steel wall and gaps with 1 to 2 mm width were found everywhere.

The paper from Kang et al was presented by S.B. Kim. It deals with the quenching of 30 to 40 kg Al_2O_3 and iron in water under 1.7 MPa ambient pressure in the LAVA test facility. a gap was formed at the interface between the debris and steel wall. A significantly rapid temperature reduction, probably due to water ingress, occurred only in the test with ceramic melt but not in case of metallic melt.

The paper presented by Sehgal describes the FOREVER test facility which employs a 1/10 linear-scaled carbon steel vessel. It is planned to perform experiments with 20 litres binary oxidic melts to study gap formation due to vessel creep. Gap cooling experiments will then be performed. Scaling considerations have been investigated and pre-test calculations have been performed with MVITA and ANSYS codes, respectively, for thermal loadings and for creep behaviour.

Strizhov presented the paper of Kobzar et al, which deals with a separate effects test for gap cooling. Varied parameters are height and width of gap, ambient pressure, hydrostatic head and one or two sided heating. At higher heat flux periodic oscillations with very low frequency were observed. Two side heated gap locally dries out at 30 % less power than one side heated gaps. Experiments with inclined gaps are planned.

S.B. Kim presented the paper of Jeong et al. It deals with various small scale experiments to visualise the gap flow and to measure the maximum heat flux for gap dry-out (CHFG test series). The gap dried out at relatively low power compared to other experiments. The dependency of dry-out on pressure is relatively weak (Koizumi correlation).

The paper presented by Koehler deals with a large scale experiment with gap cooling in a TMI-2 like configuration. Varied parameter are gap width, pressure, sub-cooling and heat flux (max 550 kW/m²). High heat fluxes are realised with small gap widths. After start of the heating often periodic oscillations with 1/20 to 1/30 Hz are observed. The pressure amplitude corresponds to static head difference between liquid and vapour filled gap.

During the concluding discussion of the session, the following main points were raised :

- The formation of gaps with a width in the order of a couple of mm has been confirmed after relocation of corium melt masses up to 200 kg in ALPHA, LAVA, FAI and FARO experiments.
- The total power transfer to the fluid in narrow gaps is limited by dry-out rather than critical heat flux.
- The measured maximum heat flux (100 to 500 kW/m²) which results in gap dry-out increases with gap width, pressure and sub-cooling. At higher heat flux longer local dry-out periods result in wall temperatures higher than Leidenfrost temperature and spontaneous re-wetting is not possible.
- Discrepancies regarding the dependency of maximum heat flux on pressure between different test facilities should be investigated.
- Internal gap cooling requires long-term availability of water and stable crust formation. The latter is questionable for larger melt pools and for metal-rich melts. The tendency of better cooling conditions at higher pressure due to gap formation and higher heat flux is contrary to depressurisation as severe accident measures. Its safety relevance was questioned, nevertheless internal gap cooling seems to be important for specific sequences, as seen in TMI-2.

3.2.4 Creep behaviour of reactor pressure vessel lower head

The objective of this session was to understand the creep behaviour of the RPV lower head under the combined effect of pressure and temperature. Thus, enhancing our knowledge of the gap formation between the RPV lower head vessel wall and corium crust, and more importantly, if RPV lower head were to fail, what would be the size, location and time to failure.

Five papers were presented in this session, one experimental and the remaining four analytical.

The paper presented by T. Y. Chu discusses experimental investigation of creep behaviour of RPV lower head under the combined effect of pressure and temperature performed at Sandia National Laboratories (SNL) on a 1:5 scaled lower head. Size, location and time to failure depend on the heat flux distribution on the inside of the lower head. It appears that the failure location might be related to slight variations in the wall thickness caused by manufacturing of the vessel.

In the paper presented by Autrusson, two simplified models were proposed to estimate the creep rupture of the RPV lower head for the flooded and dry cavity. Application of these models to SNL's lower head failure experiments are presently underway.

Strizhov presented the paper by Yamshchikov et. al., dealing with application of finite element code (HEFEST) to SNL's first two lower head experiments. Result of this analyses was supplemented with the studies of uncertainties of the prediction with LOHEY code.

In the paper presented by Sievers results of a parametric study concerning the influence of the wall thickness on the creep behaviour of spherical shells simulating the RPV lower head were summarised. It shows that creep failure in a scaled thin shell under adequate loading conditions is reached much earlier than in a RPV lower head, because significant temperature gradients are build up in the thick shell.

The paper presented by Bhandari deals with the mechanical behaviour of the RPV low-alloy steel materials in late phase external cooling during a severe accident. The long-term cooling introduces strong stress changes which may result in local damages progression. The consequences of this must be investigated.

During the concluding discussion of the session, the following main points were raised :

- Further knowledge of the RPV lower head material properties are needed for adequate modeling of strain and stress behaviour.
- Additional integral RPV lower head structural integrity experiments scaled properly for wall thickness need to be carried out.
- Further experimental study on the RPV lower head creep behaviour needs to be performed at lower pressures.

3.2.5 Ex-vessel boiling and critical heat flux phenomena

The objectives of this session was to quantify the heat transfer of ex-vessel flooding.

Two experimental papers were presented in this session, one including analytical work.

The paper presented by Cheung deals with 0.3 m diameter ex-vessel boiling experiment. The buoyancy driven co-current two phase flow induced by the boiling process in the annular channel enhanced nucleate boiling heat transfer coefficient along the hemispherical downward surface.

The paper presented by Rouge deals with the analytical full scale forced convection experiment SULTAN with a wide range of parameters. CHF results obtained on SULTAN are consistent with those obtained on ULPU. Based on the measured data a Critical Heat Flux (CHF) correlation were developed, in terms of pressure, mass velocity, steam quality, gap width, and gap inclination. 3-D simulation with the CATHARE code of SULTAN experiment showed the capability of revealing the 3-D effect in the experiment.

During the concluding discussion of the session, the following main points were raised :

- The experiments confirmed high heat transfer coefficients for ex-vessel boiling.
- The plant specific design of RPV, cavity and insulation structure have important impact to the maximum heat transfer to the external coolant. The gravity driven flow is sensitive to steam venting.
- Feasibility studies of ex-vessel cooling must consider the effect of reduced heat transfer due to degradation of insulation, unavailability of flow paths, etc.

3.3 Scaling to reactor severe accident conditions and reactor applications

The session consisted of three papers on in-vessel retention of PWRs by external flooding and of two papers on the BWR lower head penetration failures.

Rempe presented the paper summarising the U.S. NRC sponsored review of Prof. Theofanous' report on in-vessel retention (IVR) and coolability for AP-600 like design. The impact of different material properties and melt configurations on IVR were included.

C. Cognet reported the application of MAAP4 to study in-vessel retention of a large PWR by external flooding. He concluded that the study was not capable of demonstrating sufficient thermal margins to support the in-vessel retention concept for all severe accident scenarios.

Caroli reported the analyses on thermal hydraulic behaviour of the molten pool and thermal conditions of the vessel wall for three different melt configurations in a PWR vessel lower head with penetrations.

Lindholm reported the Nordic study for a BWR concerning the debris bed formation, the debris bed cooling by reflooding and the likely failure mechanism of the lower head. The work was done by comparing predictions with integral codes MAAP4 and MELCOR, and by applying specific thermal and structural code PASULA for the lower head failure predictions.

Stempniewicz reported two studies aiming at prediction of the BWR lower head penetration failure. The first part dealt with the finite element ANSYS analysis of the CORVIS drain line experiments. The second part studied lower head penetration failures of GKN Dodewaard with MAAP and MELCOR codes.

During the concluding discussion of the session, the following main points were raised :

- The results and the extensive expert review process of the AP-600 in-vessel retention study have been presented and discussed.
- The reasonability of applying integrated severe accident codes for physical studies has been demonstrated. It was recognised that integrated codes are sometimes applied outside their original scope and that the practical assessments and decisions concerning severe accident management require sound physical understanding of the phenomena that can be obtained through separate effect experiments and analytical work.