NEA/CSNI/R(97)30

OECD/CSNI SPECIALIST MEETING ON FUEL COOLANT INTERACTIONS

Summary and Conclusions

JAERI – Tokai-Mura, Japan
19-21 May 1997

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS
OECD NUCLEAR ENERGY AGENCY
Le Seine Saint-Germain – 12, boulevard des Îles
F-92130 Issy-les-Moulineaux (France)
Tel. (33) 1 45 24 82 00   Fax (33) 1 45 24 11 10

Unclassified **NEA/CSNI/R(97)30**

OECD
OCDE
PARIS

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

OLIS : 10-Mar-1998
Dist. : 12-Mar-1998

English text only

NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

OECD/CSNI SPECIALIST MEETING ON FUEL COOLANT INTERACTIONS

Summary and Conclusions

JAERI - Tokai-Mura, Japan
19-21 May 1997

62929

Document incomplet sur OLIS
Incomplete document on OLIS

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article I 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 all OECD Member countries except New Zealant and Poland. The Commission of the European Communities takes part in the work of the Agency.

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.

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 meeting.

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.

OECD/CSNI Specialist Meeting on Fuel Coolant Interactions

May 19 - 21, 1997, JAERI-Tokai, Japan

MEETING SUMMARY

1. Introduction

Research activities and interest on fuel-coolant interaction (FCI) have been increased and broadened since the last CSNI Specialist Meeting held in January 1993 in Santa Barbara(U.S.A.). Significant experimental and analytical research has been performed in many OECD countries including France, Germany, EU (JRC), Japan, U.K. and U.S.A. Research has also been initiated or is being planned in other countries, such as Korea, Russia, and Sweden. The growing international interest is, in large part, due to the emphasis on broader aspects of FCI ranging from melt quenching and coolability to energetic explosions (both in- and ex-vessel), and their relevance and applications to next-generation reactor design as well as accident management strategies.

The objectives of the meeting are categorized as follows:

(1) to review our knowledge and to obtain consensus on the phenomenology of FCI and in predicting FCI behavior in LWRs severe accidents.

(2) to identify those areas of FCI phenomena and prediction which are important for reactor safety but still poorly understood and require further study with clear methodologies.

(3) to inform the community and the regulatory agencies of the status of FCI issues, especially in the application to accident management and future reactor designs.

The proposal for this meeting was initiated from CSNI PWG2, but the scope includes ex-vessel fuel-coolant interactions; thus the meeting was also supported by PWG4. The meeting was organized in collaboration with the Japan Atomic Energy Research Institute (JAERI). There were a total of 36 papers, and 80 specialists from 13 countries and 1 international organization attended the 3-day meeting.

The submitted abstracts and papers were thoroughly reviewed by Programme Committee members(M. Akiyama, D. Magallon, S. Basu, H. Jacobs, G. Berthoud, T.G. Theofanous, B.R. Sehgal, K.H. Bang, J. Sugimoto and N. Yamano) and additional lead reviewers(D. F. Fletcher, M. Buerger, D.H. Cho, M. Corradini and S. Kondo). They chaired the sessions in the meeting. It should be noted that their devoted contributions were also essential to finalize this meeting summary.

2. General Technical Remarks

The followings are general technical introductory remarks, observations, comments and recommendations, intended as a high-level summary of the meeting:

(1) In the proceedings of this meeting, addressing issues from reactor applications to fundamentals, we find no new evidence that would change or violate the conclusion of SERG-2 (1996) that alpha-mode failure is not risk significant.

(2) Significant progress has been made since the Santa Barbara meeting (1993) in experiments (including instrumentation), basic understanding and analysis/code development as described in detail in Section 3. It is also noted that continued close coupling between the experiments and the analyses should be pursued in order to establish the physically-based mechanistic modeling.

(3) Several areas have been identified, which need further investigations to understand the basic FCI phenomena, and to improve the modeling. Such investigations should have close relationship to reactor applications, e.g., accident management (ex-vessel or coolability), future reactor designs etc., as described in detail in Section 3.

(4) We recommend maximizing open communication between various research groups in order to accelerate the resolution of the remaining issues. The OECD can contribute significantly to this process by organizing, for example, standard problem exercises.

(5) We recommend that the next specialist meeting be held within 3 to 5 years in order to synthesize the activities described above.

3. Detailed Conclusions and Recommendations

The followings are more detailed conclusions and recommendations summarized by session chairpersons:

3.1 Reactor Applications

3.1.1 Summary of Papers

Five papers were presented in the session on reactor applications including an overview paper by Basu et al. on the current understanding and the future research needs in FCI. The overview paper discussed the SERG-2 findings on the resolution of the alpha-mode failure issue namely, that the issue was considered resolved from the risk perspective. The paper also identified a number of residual FCI issues pertinent to debris coolability (both in- and ex-vessel), lower head integrity under steam explosion loads, and ex-vessel steam explosions as a potential consequence of accident management measures. Current understanding of FCI phenomena, i.e., melt jet breakup, premixing, triggering, and propagation were discussed and finally, recommendations for future research in FCI were provided.

The paper by Zuchuat et al. gave an account of the steam explosion-induced containment failure studies for operating Swiss nuclear power plants (both BWRs and PWRs). Plant-specific geometries were considered in the paper and both in-vessel and ex-vessel steam explosions were investigated. Using the current knowledge of FCI phenomenology, upper bound and best estimate failure probabilities were computed for the plants under consideration. Based on the computed values, it was concluded that the conditional probability of having containment failure is very unlikely in all cases under accident scenarios of interest.

The paper by Theofanous et al. presented a comprehensive treatment of the AP600 lower head integrity issue under steam explosion loads and concluded that for accident scenarios of interest, integrity of the lower head would be assured. The comprehensive treatment took advantage of the additional insights gained into premixing and propagation research since the OECD/CSNI Specialist Meeting at Santa Barbara in 1993, and also of extended validation data bases for the premixing code, PM-ALPHA, and the propagation code, ESPROSE.m. These factors were brought together in a Risk Oriented Accident Analysis Methodology (ROAAM) framework to evaluate the likelihood of lower head failure with the conclusion that the failure is physically unreasonable.

he paper by Almstrom et al. presented by Frid discussed a simplified approach to incorporate the effect of fluid-structure interactions in the calculation of the containment response to ex-vessel steam explosions. In this approach, a coupling between explosion loads and cavity wall response is considered through a shock-structure interaction mechanism. In contrast, in the conventional approach to structural response calculations, the cavity wall is considered rigid and shock- structure interaction is neglected. The paper concluded that the new approach gives a more realistic cavity wall response.

The paper by Kolev presents a comparison between IVA4 simulations and FARO L14, L20 experiments. Both experiments were performed with the same geometry but under different initial pressure. The strong effect of the volume expansion of the evaporating water at low pressure is demonstrated. An in-vessel simulation for a large PWR was presented. The insight gained from this study is: that at no time are conditions for the feared large scale melt-water intermixing at low pressure in force, with this due to limiting effect of the expansion process which accelerates the melt and the water into all available flow paths.

3.1.2 Chair's Summary of the Session

(1) Significant progress has been made in FCI-related experiments, models, and code development since the OECD/CSNI Santa Barbara meeting in 1993 leading to an improved understanding of the basic FCI phenomena, and practical implementation of such understanding to resolve the relevant reactor safety issues.

(2) The information presented at the meeting offer no new evidence that would change or violate the conclusion of SERG-2 that alpha-mode failure is not risk significant.

(3) Current FCI issues of relevance to reactor safety are: debris coolability (both in- and ex-vessel), and localized energetic FCI with implications to RPV lower head integrity.

(4) Based on the current understanding, energetic steam explosions in reactor geometries and with reactor prototypic materials cannot be excluded at present. Triggering of prototypic materials may be difficult and triggerability at high pressures may be reduced but the data base is far too sparse to verify these conjectures. Also, reduced triggerability does not necessarily imply reduced explosivity. Therefore, in reactor applications, explosivity cannot be eliminated and hence, energetics and consequential extent of damage from localized FCI must be considered and properly assessed.

(5) Finally, in reactor applications, specifics of the system and accident scenarios must be considered in order to realistically evaluate the consequences of energetic FCI.

3.2 Premixing (I)

3.2.1 Summary of Papers

This first session on the pre-mixing phase of fuel coolant interactions (FCIs) contained four papers. Two of the papers dealt with experiments performed, respectively in the QUEOS and the MAGICO facilities. The other two papers dealt with development and validation of analysis methods.

The paper by Meyer describes the results of experiments on pre-mixing conducted in the QUEOS facility at FZK, with 7 to 20 kilograms of hot spheres. More than 40 experiments were performed, characterized primarily by relatively high particle fractions. Data of seven experiments with sphere temperatures of 1800 K were presented and compared with results from experiments with cold shperes. Data obtained included pressures, steam flow rates, water levels and several series of photos taken from high speed films(due to technical problems the movies could not be shown). For one recent experiment(2550 K) void fraction distributions measured with local void probes were presented. The main observation from the experiments was that the steam hole created by the leading spheres facilitated the passage of the latter spheres, which joined up with the leading spheres and accelerated their passage through the water. The experiments found extensive water depletion zones, however, regions of low void fractions interacting with the spheres were also observed. The QUEOS experiments have used much larger melt volume fractions than the MAGICO experiments (next paper) and the results obtained in QUEOS are somewhat different than those from the MAGICO tests.

The paper by Angelini et al. describes the regimes of premixing obtained by MAGICO experiment. The MAGICO-facility has been upgraded to perform experiments with spheres at temperatures up to 2000 K. Several experiments have been performed with up to 6 kilograms of hot spheres. The

MAGICO tests provided the ideas on water depletion, which have been used for the models incorporated in the PM-ALPHA code. The MAGICO tests were performed with melt-particle volume fractions substantially lower than those used in the QUEOS tests. Still, extensive water depletion regions were observed. Excellent video movies were presented. X ray pictures provide detailed void fraction and particle volume fraction distributions, for use in code comparisons. The test results shown by Angelini distinguished the regimes of pre-mixing dominated by the inertial and the thermal effects. The latter pre-mixing regime was produced by using low volume fraction pours of hot particles.

The paper by Jacobs et al. examines the constitutive relations for drag incorporated in the IVA-KA code. The IVA-KA code is a modified version of the IVA code developed at FZK-INR by Kolev. This paper also reports a new model for radiative heat transfer incorporated into the IVA-KA code. The adequacy of these models is judged through very strict comparisons of the code predictions with the data obtained in the QUEOS tests. The drag model currently employed might be improved by accounting for the effects of strongly accelerated relative motion. The radiation model is based on the distribution of fractional energy absorbed in water with thickness of water layer, as calculated by Fletcher. The authors are satisfied with the results obtained. The authors found that numerical diffusion is potentially very disruptive in their calculations using a first-order donor-cell scheme. This became evident when modeling the free fall of an initially less than 5 cm high layer of particles over a distance of 1.3 m in the QUEOS experiment.

The very large paper by Theofanous et al., extracted from the report DOE/ID-10504, describes the very large effort employed in verifying the PM-ALPHA code, which provides a description of the pre-mixing phase of the steam explosion process. The code predictions are tested against analytical solutions and data from the MAGICO, QUEOS, MIXA and FARO tests. Analysis of a number of QUEOS tests are reported. The multifield aspects of the PM-ALPHA code are verified step by step. The PM-ALPHA code does not model the jet break up process mechanistically. Instead, the authors employ a parametric representation, which they currently claim as adequate for their purposes. The PM-ALPHA code has been used, successfully, in the evaluation of the in-vessel steam explosion loads on the lower head of the AP-600 vessel. The authors have been able to control the numerical diffusion in this basically Eulerian- description three dimensional code. The comprehensive verification achieved for the various code models is impressive.

3.2.2 Chair's Summary of the Session

(1) Clearly, the pre-mixing phase of the FCIs is important since it is the precursor of the subsequent phases. Much work has been done lately and significant progress has been achieved in both the experimental information obtained and the modeling developed. The MAGICO and the QUEOS experiments, both have achieved great strides in increasing the particle mass and

temperatures, and improving the instrumentation employed.

(2) The outstanding outcome of the recent progress is the confirmation and the prediction of the water depleted zones in the pre-mixtures, which limit the extent of pre-mixing, thereby inhibiting large steam explosions. Perhaps, a consensus on this could be reached, inspite of the differing opinions on the inferences from the QUEOS experiments.

(3) The PM-ALPHA , IVA-KA, MC-3D and the other codes which model the pre-mixing phase are all multidimensional, three or four phase codes. The PM-ALPHA is the only code, which has been extensively verified to date, although other codes are following the same path. It must be stated that as a general rule; the more detailed the formulation, the more detailed the information required to bring closure to the formulation. A collective set of constitutive relations may provide reasonably-correct predictions for a particular set of pre-mixing conditions, and not for another set. The dynamic separate-effects experiments would be designed to test the key individual constitutive relations.

(4) There are differences of opinion on how the source for pre-mixing phase, i.e., the jet break-up (atomization) should be treated. The jet break-up process is part of the pre-mixing phase and should be treated as such i.e., integrated with the development of the pre-mixture. The current database (with hot particles in water) should be more focused on a true melt jet interacting with a coolant pool.

(5) Another aspect, which is mentioned previously, is the model validation, for pre-mixing of melt (particles or jet) with highly subcooled water, as may occur in ex-vessel steam explosion scenarios. These scenarios are of higher concern for BWRs; with their small containment, already considerably stressed by the hydrogen generated. The in-vessel steam explosion (with saturated water), credible only for a PWR, has extremely low probability of causing early failure of the containment.

3.3 Premixing (II)

3.3.1 Summary of Papers

In the paper by Magallon et al. the FARO experimental results were reviewed with the main emphasis on the comparison of data for the high pressure test series conducted over the last five years; i.e. L-6,8,11,14,19,20 and most recently L-24. The test results clearly show a dependency of the degree of melt quenching on the water pool depth and the ambient pressure with more second-order effects observed for the fuel mass [on a per unit mass basis]. The role of melt composition was the most apparent effect with test L-11, which clearly indicated the effect of zirconium oxidation and associated hydrogen production. The role of hydrogen generation in general was the main topic of discussion with further work being needed to identify if the hydrogen generation observed in FARO is test specific or generic to all oxide melts even at accident conditions.

In the paper by Yamano et al. melt jet breakup was studied in the framework of the ALPHA test program, by using simulant materials [Pb-Bi eutectic melt] in jet quenching tests. Results and analysis of the first two tests were presented for jet quench in a deep pool of saturated water. Steam generation rates as well as jet breakup length and post-test debris size distributions were also measured. The behavior observed in these first two tests were also predicted with the JASMINE code, which is being developed at JAERI for use in simulation of steam-explosions. Agreement with the observed data was reasonable [as well as comparison with FARO L-14] and served as a good starting point for further analysis.

The paper by Addabbo et al. provided a synopsis of the key results from the ISP-39 exercise organized and conducted by the JRC Ispra. This standard problem, ISP-39, was to benchmark the predictive capabilities of computer models used in the evaluation of FCI mixing and quenching phenomena and compared with the FARO L-14 test results. The preliminary assessment of the results from the ISP-39 code exercise has shown a wide spread in the predictive capabilities of FCI mixing models. Pending more detailed analysis, it appears that the general adequacy of FCI modelling decreases with the progression of the phenomena. This work sparked a good deal of discussion about the need and usefulness of open comparisons of analysis and test results.

The paper by Dinh et al. at RIT in Sweden presented by B.R. Sehgal focused on a review of past jet breakup phenomena, the conduct of simulant tests to visualize the phenomena and new phenomenological modelling of the mechanisms for jet breakup. The results of the review and the scoping tests have led the researchers to the conclusion that film boiling along the jet surface does not lead to an accumulation of a large amount of vapor which can significantly aid in the breakup process; i.e., a laminar film boiling model with vapor departure is more physically relevant than other pictures. This along with extensive stability analysis has led the group to begin to model the jet breakup process from the concept that the jet momentum and associated momentum transfer dominates the observed behavior. This implies a complete multi-dimensional CFD approach is warranted to gain further insights.

MC3D code for premixing calcualtion was introduced by Dr. Berthoud. The basic structure of the code and numerics were discussed and the code's prediction of FARO L-14 test was presented. MC3D has a four-field model in which melt jet and droplets are treated as separate fields. The paper reported that this four-field application of MC3D showed better prediction of FARO L-14 test data than the typical three-field model. The current results were found to be promising although further validations of jet breakup model and heat transfer models are necessary.

The main thrust of the paper by Fletcher et al. was to remind the researchers the basic requirements of any analysis that uses computer modelling and multi-dimensional computer modelling in particular. The subject of numerical diffusion was discussed in some length in the context of multi-dimensional Eulerian simulations of multi-phase or multi-fluid flow. Fletcher reviewed a series of techniques that are used to minimize the numerical diffusion of such analysis and made specific recommendations for use in FCI mixing and propagations formulations. Lagrangian considerations were not directly discussed.

The VESUVIUS FCI computer model was presented by Vierow. The basic equations and modelling assumptions were discussed in detail for this multi-fluid multi-dimensional Eulerian formulation. In addition the computer model was compared with specific simulant tests and the FARO L-14 test. The current results of such comparisons were found to be promising with improvements identified.

In the paper by Buerger et al. various descriptions of jet and drop breakup are considered, which are applied in FCI mixing codes. Jet breakup processes are predicted by the IKEJET model and open questions were discussed in the paper. The major question is how to model the jet breakup process in the presence of a thick and turbulent vapor film around the jet body. In contrast to the previous paper of Dinh et al., the IKEJET model assumes that the vapor will accumulate along the jet body and then considers the breakup processes under this physical picture. The application of IKEJET to breakup of hot melt jets yielded too little breakup and quenching if multiphase effects on the wave growth and stripping processes due to entrainment of water and melt were not considered. It was demonstrated that inclusion of these effects may be sufficient to explain the experimental behavior.

3.3.2 Chair's Summary of the Session

(1) The degree of radiation transport into the multiphase coolant and the associated degree of energy absorption [and steam generation] needs to be clarified with a correct methodology. This can have a large impact on mixing.

(2) Jet breakup in a multiphase environment needs to be modeled on a physical basis, not parametrically.

(3) Larger scale FCI experiments (e.g., FARO, ALPHA) could be used to investigate integral mixing and explosion phenomena with proper measurements; i.e., diagnostics must be further developed to reveal mixing details.

(4) Can an ISP be used as a mechanism for open communication for differences in physical models of FCIs? This has to be discussed for future CSNI activities since no clear consensus was reached in the session discussions.

(5) One must account for (correct for) numerical diffusive effects in Eulerian formulations of mixing processes. Lagrangian models may hold better promise for multifluids, multiphase and multidimensions.

(6) How much information can be obtained from post-test debris data in quench tests? Can we use

debris morphology to distinguish surrounding conditions for the time of breakup? These questions need to be discussed to obtain data usefulness.

(7) Reactor plant applications must be considered when determining what physical effects of the FCI require further experimental/analytical consideration:

- Trig. of reactor materials and escalation.
- Fuel debris sizes/spreading.
- Explosion energetics and dynamic pressures.

3.4 Propagation/Trigger

3.4.1 Summary of Papers

Triggering is a complex process which depends on the localized behavior of a small amount of melt. The mechanisms by which triggering can occur are not well understood and it is not possible to predict whether triggering will occur in a given situation or not. However, there is experimental information from which the likelihood of triggering can be judged. There is a general consensus that the prediction of the triggering phenomenon will always remain restricted, due to its stochastic nature.

New computational techniques (particularly the CIP and MPS methods) have allowed fundamental studies of the thermal fragmentation process, which follows vapor film collapse (paper by Inoue). These are providing insight into the mechanisms which operate, with the initial studies appearing to support melt jet formation as proposed by Ciccarelli and Frost. However, the underlying mechanism appears to be different, in detail (water jet formation at thicker parts of vapor film, no direct splash formation from impact, splashing due to strong evaporation in low pressure region around original thin film region and in original water jet regions based on fine scale Taylor instabilities). This work should provide useful input into the construction of simplified, physically-based, thermal fragmentation submodels for use in propagation codes.

KROTOS tests using UO2/ZrO2 melt have shown very different behavior from the earlier tests using alumina (paper given by Magallon). It has not been possible to achieve propagating energetic explosions using the same trigger as in the alumina experiments. Only weak propagating events have recently been obtained in tests with initial pressure increased to 2 bar as well as with a larger mass of melt(5 kg) at 1 bar. Already for the premixing behavior, the different melt materials yielded significant differences, with increased void fraction, melt fragmentation and presence of hydrogen in the case of UO2/ZrO2 melt. The cause of the differences is not yet clear. Candidates are physical properties of the melt (density, thermal properties) or chemical processes (hydrogen). Finer fragmentation, stronger steaming and the existence of hydrogen also yield explanations for difficulties in triggering. The increase in pressure, reducing the void, may favor triggerable mixtures although in general making more difficult the triggering process.

The capability and validation of ESPROSE.m 3D, the only multi-dimensional propagation model already used in various reactor simulations, has increased enormously (paper by Theofanous). An extensive validation exercise has been carried out using analytic solutions, characteristic and numerical solutions and comparison with data from a range of KROTOS tests. This validation has tested the codes ability to predict reflected waves at walls, behavior at free surfaces with variation of the voiding in the mixture, and to simulate propagations ranging from weak to supercritical. Given that the calculation of propagations in two or three dimensions introduces no new physics, the need for multi- dimensional experiments has been reduced.

The database on microinteractions (relative velocity fragmentation at pressures relevant to supercritical propagations) has increased significantly (paper given by Theofanous). In particular, the experiments with single steel drops yield a further step to real conditions. Using predefined voids in the water allowed then to obtain considerably higher relative velocities and Bond or Weber numbers determining the fragmentation process in strong thermal detonation waves. Plans for experiments involving UO2 and ZrO2 melts are well-advanced at Santa Barbara. There is general agreement that energy transfer modeling from the melt to the coolant, following fine fragmentation, must account for the fact that not all of the water is involved (the basis of the microinteractions concept).

Other codes, as MC3D, also take into account heated and unheated coolant phases (paper given by Berthoud). With a different formulation than in ESPROSE, 1D and 2D calculations for the KROTOS 21 tin experiment have been performed with MC3D, varying the fragmentation rate and heat transfer. The fragmentation is based on an approach for thermal and hydrodynamic fragmentation with parameters still to be adjusted and the heated part of water is determined on the basis of transient heat transfer considerations, in contrast to linking it to the fragment cloud volume as in the microinteractions approach of ESPROSE. The fragmentation as well as the transient heat transfer laws need further elaboration.

3.4.2 Chair's Summary of the Session

In summary, progress in the areas of triggering and propagation has been good. We are gaining a much better understanding at the microphysical level and the tools needed to make reactor scale simulations are becoming very advanced and well-validated. In addition to ESPROSE.m, other codes, e.g. MC3D, have also started a validation process and first applications to reactor conditions. New experimental data for reactor materials, both at the single droplet and approximately 5 kg scale, is being generated and promises to make a valuable contribution in this area. One area which needs to be filled in, is the generation of microinteractions data for escalation conditions. In general, the specific formulation of the microinteractions laws in thermal detonation codes appears to require further data and elaboration concerning the fragmentation as well as the part of heated water.

3.5 Experiments

3.5.1 Summary of Papers

Seven papers were presented in the session concerning various open problems in understanding premixing as well as steam explosion triggering and energetics.

In the presentation by D. Cho, ANL, hydrogen generation and chemical augmentation of steam explosion energetics was addressed on the basis of experiments with Zr and Zr-ZrO2 melts. High energy conversion ratios (up to 10%) were calculated from the tests if no chemical energy was assumed to have been released during the interaction. Low energy conversion ratios (< 2%) were calculated if all the Zr oxidation observed was supposed to have contributed. The uncertainty comes from the fact that the quantity of hydrogen was measured some time after the interaction. Thus, it is not possible to determine when the Zr was oxidized. Anyway, the chemical energy release (up to 90% of the potential chemical energy) was not effectively converted into mechanical work. It was concluded that modelling effort was needed to elucidate the relevant energy conversion process.

M. Corradini, UW, reviewed and analyzed steam explosion experiments with Sn, Al2O3 and Zr/Zr-ZrO2 melts performed at JRC Ispra (KROTOS), University of Wisconsin (WFCI) and Argonne National Laboratory (ZrEX, see above). A result of the work was that an optimum constraint seems to exists, which maximizes the energy conversion. It was further noticed that steam explosions had maximum energy conversion at high volume of mixture to volume of fuel ratios (of the order of 10-20). The maximum efficiency, obtained with alumina melt, was ~ 3% of the total energy available, while efficiencies remained below ~0.5% with tin. The question was raised why these efficiencies are so low with respect to thermodynamic values and whether or not they bound the range of expected reactor material behavior.

R. Bonazza, UW, presented studies on the suppression of stratified steam explosions due to a high void obtained by injecting air into the coolant pool (R134a) before flooding it with the melt (hot water). It was deduced from the experiments that the steam explosions were suppressed for void fractions above approximately 30%.

K. Sugiyama, HU, reported on the observation of entrainment and/or entrapment of water into crusted melt jets in tests involving molten tin and molten zinc dropped into water. The large-scale conical shape structures which form on the jet during its descent through the water are capable, for hydrodynamic reasons, of entraining (tin) or entrapping (zinc) water. Thermal interactions result which disrupt the structures and this was suggested to be a possible triggering mechanism for steam explosions.

A. Kaiser, FZK, presented results of melt water interaction tests (PREMIX 10 and 11) involving 20 kg of alumina melt poured into 0.5 m deep saturated water pools. The single jet test PM-10 resulted in a classical premixing and quenching of the melt as always observed so far with alumina melt and saturated water both in the PREMIX and the KROTOS test facilities when no external trigger is applied. On the contrary, a low-efficiency (low constraint) spontaneous steam explosion occurred in the triple-jet test PM-11. The explosion occurred after the melt had partly settled on the bottom. Local void measurements indicated the accumulation of a large volume of water above the catcher pan just before the steam explosion occurred.

R. Sehgal, RIT, presented experiments with binary oxide melt droplets falling into a water pool. The influence of melt freezing and film boiling conditions on droplet deformation and fragmentation was studied. It was found in particular that if the melt temperature is between the liquidus and solidus (so-called "mushy" zone) or if film boiling is stable because of low subcooling, droplet deformation and fragmentation are reduced (or even suppressed). For UO2-ZrO2/water systems fast transition of melt to the mushy zone and formation of stable film boiling due to high radiative heat transfer might play a fundamental role in mitigating steam explosions.

T. Dinh, RIT, presented investigations of film boiling on the surface of high temperature melt jets or melt droplets. He came to some controversial and debated conclusions concerning film thickness, film boiling regime and the role of radiation absorption by water. These ideas were developed on the basis of the analysis of a number of past experiments on film boiling in various conditions, and on a numerical study in which the effects of water subcooling, radiation heat transfer and temperature-dependent steam properties were analyzed. For high temperature conditions of the melt (reactor type materials) he expected a thin film (1-3mm) with a wavy vapor-liquid interface and departure of bubbles. Due to the low density and high dynamic viscosity of the steam at high temperature, the vapor film should remain laminar. The deep penetration of radiation into water at high surface temperature should reduce significantly the effect of water subcooling on film boiling.

3.5.2 Chair's Summary of the Session

The presentations demonstrated that some aspects of steam explosions are far from being well understood. For example, more data with prototypical materials would be particularly helpful.

3.6 Code/Models

3.6.1 Summary of Papers

In this session seven papers were presented, three of them being devoted to detailed models useful for FCI calculations while the four others presented calculations of premixing and explosion with different computer codes.

In the paper by Kolev, a semi empirical film boiling model to be used in the IVA 4 code was presented. First, film boiling on a vertical plate is studied taking into account the instable structure of the vapor film due to Kelvin Helmholtz instabilities, as observed in experiments using long plates. As this model is to be used at high temperature, particular attention is given to the treatment of radiation. This model is successfully compared with averaged heat transfer coefficients obtained at the Swedish Royal Institute of Technology with a maximum wall superheat of 1236 K. Then the method is extended to the sphere case and compared with the experimental database of Liu and Theofanous, who produced data in single and two phase flow configuration. In this case, all the cases show an error band of about 30 %, the error band being reduced to + 20 to - 15 % in the case of single phase saturated water.

In the paper by Koshizuka et al. thermal fine fragmentation occurring during steam explosion is studied using a new numerical method : the Moving Particle Semi-implicit method based on moving particles and their interactions. This method has been extended from the case of incompressible flows to the cases in which evaporation is occurring. In this case, new particles are created. Two evaporation models have been developed : normal boiling and spontaneous nucleation. This model has been applied to study the effect of coolant jet impingement resulting from film destabilization on molten fuel. In the case of a water jet on coolant, it is shown that entrapment of water into the fuel, as in Kim's model, is not likely and that fragmentation should follow the production of melt filaments (Splash theory of Bankoff or Ciccarelli - Frost observations). However, entrapment would be possible for a jet density higher than the melt one.

The work by Corradini et al. deals with the improvements included in the TEXAS FCI code to deal with dynamic fuel fragmentation during the mixing and explosion phases of a steam explosion. The main improvement was in the jet breakup model during the premixing phase. In addition to the past Rayleigh Taylor Instability model at the "jet" leading edge, fragmentation by Kelvin Helmholtz instability along the jet column and Boundary Layer Stripping at the "jet" leading edge have been incorporated in TEXAS V. Parametric calculations for the FARO L 14 experiment show that fragmentation by Kelvin Helmholtz type instabilities should be the dominant mode of fragmentation.

In the paper by Annunziato et al. results of pre and post test calculations of the FARO premixing experiment and of the KROTOS explosion experiment with COMETA and TEXAS codes available at JRC Ispra are presented. As hydrogen has been found both in the FARO and KROTOS experiments, emphasis is put on the effect of hydrogen in these processes. In particular, hydrogen production (using different production models) is shown to be responsible for an overpressurization of about 5 bars in the COMETA calculation of the FARO L 20 test. The COMETA code is then used to calculate the premixing sequence for the KROTOS tests using Al2O3 (w/o the h2 production model) or UO2-ZrO2 melt. In the UO2-ZrO2 case, hydrogen production is then shown to be responsible for large voids which are not favorable for a steam explosion to occur. It has also been shown that the reaction kinetics are important; if it is very fast (metallic melt), H2 will be generated in the steam zone and not in the water leading to low voids around the melt and allowing a steam explosion to occur. A lot of parametric calculations of KROTOS 44 (Al2O3) with the TEXAS code are also presented showing the influence of specific parameters like the "minimum bubble radius" and the convective film boiling heat transfer coefficient.

In the paper by houd et al. the MC3D three fields premixing code is used to recalculate BILLEAU and the FARO L 14 experiments. This application is obviously well adapted to the calculations of experiments using solid spheres like BILLEAU. BILLEAU experiments using cold and hot (2400 K) 1 cm diameter ZrO2 spheres have been used to validate the code. It has been shown that accurate knowledge of inlet conditions is very important. For the cold test, these conditions are precisely known and the recalculations are good. For the hot tests, these conditions are not as well known but the disagreement between calculations and experiments is attributed to the description of drag and heat transfer laws in three phase flow which have to be improved. Finally, parametric calculations of the FARO L 14 experiment confirm the influence of melt entrance conditions. In these calculations, influence of the "melt jet diameter" and of melt initial droplet diameter are shown.

Calculation using the SIMMER-III code, which is a multiphase, multicomponent code written to investigate core disruptive accidents for Liquid-Metal Fast Reactor, were presented by K. Morita. Flow regime and interfacial area models in the code were detailed, with an emphasis on fuel fragmentation laws. The introduction of a film boiling model has been necessary for water calculations. Three applications were presented. Calculations of the THINA tests (FZK), using both iron rich and alumina rich thermites injected into sodium coolant; the FARO L-06 (JRC Ispra) premixing experiment involving water coolant; and the KROTOS 28 (JRC Ispra) explosion experiment in an alumina melt/water mixture were described. The present study has shown the capability of the SIMMER-III code for simulating the premixing phase both in water and sodium systems as well as the propagation of steam explosion. It was also mentioned that extensive code validation is underway through an international agreement between PNC, FZK and CEA.

The new South Korean code TRACER-II for computation of mixing and propagation phases of a steam explosion was presented by K. H. Bang. The work started two years ago with TRACER-I.

It widely uses the development made in the previous CHYMES and PM-ALPHA codes. However, some improvements in the interfacial heat transfer modeling, mainly for film boiling configurations have been developed. A special treatment for a metastable equation of state of water for supercritical conditions obtained during detonation was also presented. Then calculations of FARO L 14 premixing experiment and KROTOS 28 detonation experiment were shown. Parametric calculations changing initial values of droplet size and constant in the fragmentation model show the usual behavior obtained with other codes (large influence of these values) for premixing. The explosion calculations using initial state obtained from premixing calculations failed to reproduce the experimental pressure traces. Then, parametric uniform premixing conditions were used to better approach the experimental results.

3.6.2 Chair's Summary of the Session

(1) In this Meeting, a lot of codes (including new ones from the last Santa-Barbara Meeting) have been presented and compared with experimental results. It may then be time to analyze the results obtained by these codes in a way similar to the one used for ISP 39 (FARO L14) as presented in the Addabbo paper in session 4.

(2) As it appears that these codes are more and more qualified, it also seems that it is time to perform sensitivity analysis to determine "WHAT" is really important and "WHEN". (This has been done for some codes like IVA 4 and MC3D). These sensitivity studies have to be performed not only for global experiments like FARO and KROTOS but also for reactor applications.

(3) owever, we must keep in mind that these studies will only tell us the relative importance of the phenomena included in the codes. This is the reason why we must not rely only on code calculations.

(4) At the present stage of modelling, it appears that we still have open questions, such as

- Where does radiation go ? (the absorption of radiation from the melt into the coolant is very different in different codes)
- Do we need to describe jet fragmentation and what is the relevant physics ? (It has been recognized in TEXAS V that fragmentation along the jet column is the most important one as already mentioned in other papers in Session 4 [MC3D, IKEJET])
- What is the film boiling heat transfer for corium in two phase coolant ? (addressed in Kolev paper ; included in PM ALPHA)
- What is the influence of Hydrogen production ? (is it sufficient to explain the non explosivity of U02-Zr02 in KROTOS as expressed by Annunziato ?)
- What is the mechanism of thermal fragmentation necessary for triggering an escalation ? (see Koshizuka paper).
- What is the model for vaporization-condensation which control the escalation ?

Annex

Programme Committee

AKIYAMA, Mamoru (Institute of Apply of Energy , Japan) - Chairman

SUGIMOTO, Jun (JAERI, Japan)

YAMANO, Norihiro (JAERI, Japan)

MAGALLON, Daniel (JRC Ispra, Italy)

BASU, Sudhamay (USNRC, U.S.A.)

JACOBS, Helmut (FZK, Germany)

BERTHOUD, Georges (CEA, France)

THEOFANOUS, Theo G. (UCSB, U.S.A.)

SEHGAL, Bal Raj (Royal Institute of Technology, Sweden)

BANG, Kwang-Hyun (Korea Maritime University, Korea)

DROZD, Andre (OECD NEA) - Secretary