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NUCLEAR ENERGY AGENCY
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OECD/CSNI SPECIALIST MEETING ON NUCLEAR AEROSOLS IN REACTOR SAFETY

Summary and Conclusions

Held on 15-18 June, 1998
Cologne, Germany

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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

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

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

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of 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 consist of all OECD Member countries, except New Zealand 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.

C S N I

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

PWG4

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

FPC

The Task Group on Fission Product Phenomena in the Primary Circuit and the Containment (FPC) is a specialised extension of PWG4. Its main tasks are to exchange information, discuss results and programmes, write state-of-the-art reports, organise specialist workshops, perform ISPs in the field of fission product phenomenology.

THIRD OECD SPECIALIST MEETING
ON NUCLEAR AEROSOLS IN REACTOR SAFETY
(Cologne, Germany, 15-18 June 1998)

SUMMARY AND CONCLUSIONS

General

The Third OECD Specialist Meeting on Nuclear Aerosols in Reactor Safety was organised in Cologne, Germany, from 15-18 June 1998, in collaboration with the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH.

It was attended by sixty-five specialists representing thirteen OECD Member countries and the Commission of the European Communities. Thirty-nine papers were presented, in eight sessions. The meeting was concluded by a general discussion devoted to the following topics:

- What has been solved up to the level of plant applications and accident management?

- Where is more work needed for plant applications?

The First OECD Specialist Meeting on Nuclear Aerosols in Reactor Safety was organised in 1980 in Gatlinburg, Tennessee, United States, the second one in Karlsruhe, Germany, in 1984. They were followed by:

- an OECD/CEC Workshop on Water-Cooled Reactor Aerosol Code Evaluation and Uncertainty Assessment held in Brussels, Belgium, in 1987;

- a Marviken-V/DEMONA/LACE Workshop held in Montreux, Switzerland, in 1988;

- an OECD Workshop on Aerosol Behaviour and Thermal-Hydraulics in the Containment held in Fontenay-aux-Roses, France in 1990.

Over the last eight years significant progress has been made in source term modelling and code development. Results have been consolidated in codes which are being used for plant calculations to address safety issues. For example, two countries used their source term codes last year to assess the impact of heating from deposited fission products on the potential for steam generator tube rupture. Also, another source term code was used to assess the need of sprays for fission product removal in the proposed design of a new type of reactor. Over the next few years, experiments and model development will continue, with more emphasis on application to risk- important severe accident scenarios.

Current situation

Circuit behaviour

An important feature of aerosol formation is the composition of the particles. In this connection, there is still uncertainty as to whether reactor aerosols contain a significant proportion of CsOH. PHEBUS FP is providing information on sources from degradation under oxidising and reducing conditions, with boron carbide, in the presence of air, and from debris beds and molten pools.

The ISP40 exercise, based on a STORM test showed that aerosol deposition in pipes can be predicted within a reasonable margin of error.

The PHEBUS test results are very incomplete, as yet, but there are important indications for aerosol physics. In particular, in the circuit, all elements appear to be already in aerosol form at 700° C, with the exception of iodine and cadmium. Deposition in the steam generator was less than predicted by codes used. The significance of this difference is not clear, its consequences on accident scenarios have to be examined.

There are uncertainties about deposition, resuspension and revaporization processes in the upper head and in complex circuit structures such as steam generator tube bundles. Full-scale testing, modelling and small-scale separate-effects tests all have parts to play in reducing the uncertainties. Some full-scale tests of retention in complex circuit components under prototypical conditions indicate that significant net retention does occur.

There are indications from plant calculations that resuspension and revaporisation could have a major impact on the source to the containment. This impact depends on the specific features of the plant and the accident scenario examined. It still needs further evaluation.

In ISP40, none of the participants succeeded in coming close to the experimental results as a whole. The sizes of the resuspended particles were underestimated by all participants, perhaps because no models took account of the formation of agglomerates in the deposit layer. There is still disagreement even on which are the important parameters that affect resuspension.

Semi-empirical and mechanistic resuspension modelling are in progress to address parameters such as surface roughness, bed porosity, chemistry on the surface, and stickiness of the particles. Measurements on actual aerosols are supporting the model development.

The planned revaporisation experiments on samples from PHEBUS are expected to contribute significantly to the knowledge base on revaporisation.

Containment behaviour

Dry aerosol deposition provides an upper bound on the possible aerosol source from the containment. Further reductions can be justified based on known mechanisms such as steam condensation where appropriate conditions exist without doubt.

Different approaches to steam condensation on aerosols, in some cases, have a strong impact on predicted aerosol growth. There is evidence that a non-equilibrium treatment is necessary for proper assessment of volume condensation rates.

PHEBUS results indicate that all elements are removed from the containment atmosphere at approximately the same rate in medium-humidity conditions.

Two KAEVER tests with mixed CsI/Ag aerosols observed unexpectedly low depletion rates. The chemical composition of prototypic aerosols and the resulting degree of hygroscopicity, as evidenced by the detection of AgI in the experiments, appears to play a strong role in the depletion behaviour.

Aerosol deposition on condensing surfaces has been shown in a heat exchanger component test to depend not only on the solubility but also on the nature of the aerosol.

Flashing jets, an effective way to mobilise fission products present in the coolant, can be generated by primary circuit breaks, tube ruptures etc. High-quality data are now available on droplet size distributions and other parameters. Models predict that the resulting liquid aerosols can be effectively removed by impaction and are confirmed by integral experiments.

Design leakage from containment is the only source of fission products to the environment if the containment remains intact. Experiments show strong decontamination and partial plugging by aerosols in leak paths through electrical penetrations and flanged gaskets.

The use of hydrogen recombiners may have implications for aerosol growth and depletion, as it affects local thermal-hydraulic conditions.

Plant applications

In Europe, a large project is underway to use codes to estimate source terms for twenty key severe accident scenarios at eight representative plants.

Results of station blackout calculations by three countries were significantly different. These differences can be traced to different calculated thermal-hydraulic conditions. Based on these and other recent experiences in OECD countries, good co-operation is needed between the source term analyst and the thermal-hydraulics analyst to get reasonable source term estimates.

Where knowledge is adequate for plant application

Circuit behaviour

The modelling of the distribution of vapour condensation between wall and aerosols is now satisfactory.

The basic mechanisms of aerosol deposition in piping are well understood and modelled, except in singularities such as bends and valves. However, some of the details of these mechanisms are not well understood.

Large-scale experiments for resuspension from pipes such as PARESS and STORM have produced good quality results and documentation suitable for code purposes and there is no clear need for further generic experiments.

Containment behaviour

The experimental database on natural aerosol depletion mechanisms for containment code assessment is of good quality and sufficient. Recent experiments have employed much improved instrumentation for the characterisation of both thermal-hydraulics and aerosol physics.

PHEBUS results indicate that the deposition rates in the containment can be well predicted with a dynamic shape factor of unity, the value normally assumed.

An important effect in the containment is water condensation on aerosols, which under medium to high relative humidities (> 70 per cent) can accelerate fission product removal significantly. Recent KAEVER experiments confirm that hygroscopicity can strongly enhance aerosol deposition in the containment.

Modelling of aerosol growth in the containment is judged satisfactory when the thermal-hydraulic conditions and aerosol properties are well known.

Lumped-parameter codes predict the containment thermal-hydraulics with sufficient accuracy for simulating aerosol behaviour. In the presence of stratification and isolated flow conditions, special nodalization schemes may be required to resolve local conditions.

Remaining issues

Circuit behaviour

Circuit thermal-hydraulics are important for vapour and aerosol transport in the circuit. As an example, three independent calculations for a station blackout sequence differed considerably in the predicted fission product retentions because of differences in predicted recirculation pattems and local temperatures. It is necessary to improve confidence in predictions for flow paths, velocities and temperatures in the circuit under severe accident conditions.

There is still a need to investigate aerosol deposition in singularities such as valves and bends.

An important removal mechanism in sequences with steam generator tube rupture is flow across tube bundles. It is planned to perform scale experiments to investigate this and other potential removal mechanisms.

The ISP40 exercise results indicate that resuspension is not sufficiently understood for plant applications. PHEBUS data indicate that reactor aerosols are rather easily resuspended. Measurements of parameters such as surface roughness, bed porosity, chemistry on the surface and stickiness of the particles are needed to support the modelling development. There is a need for specific experiments related to clearly defined accident sequences, if it is required to quantify circuit retention.

Experimental work on revaporisation is scarce; theoretical and experimental development are both necessary to understand the revaporisation process.

Containment behaviour

Both detailed and integral tests are necessary to support the modelling of the removal of aerosols by sprays. Particle size and density, as well as spray droplet size, are important parameters. Removal by interacting droplets may be significant and is being investigated.

There are indications from PHEBUS that further mechanisms may play a role in aerosol removal in plants. These include turbulent impaction and charge effects and should be further investigated to scope their potential impact.

The possible impact of hydrogen recombiners on aerosol depletion rates due to affecting local thermal-hydraulic conditions and to chemical effects have to be investigated.

Pool scrubbing modelling is uneven in its level of detail (i.e., hydrodynamic models). The resulting uncertainties require review in terms of performance requirements and tolerance for uncertainty in plant applications. Coupling to containment codes is recommended.

Modelling of re-entrainment from boiling pools (a weak, but persistent late-phase source of fission products) performs well for ideal systems, but currently lacks consideration of non-ideal effects arising from suspended materials, solutes and surfactants. It has to be examined, if re-entrainment from boiling pools may have a significant effect on offsite releases.

Heat release by hydrogen burns may have a strong effect on aerosol characteristics, as a result of the thermal-hydraulic transient and can possibly liberate volatile forms of iodine. Experimental evidence and thermodynamic analysis are inconclusive as to the magnitude of the effect.

Recommendations

A meeting on the use of severe accident codes in plant calculations for source term estimation, including codes used by utilities, is recommended within the next two years.

Important experimental and analytical work is in progress on aerosol behaviour in the primary circuit; a SOAR could be productively undertaken in this area, within two years.

In light of substantial recent work completed on aerosol behaviour in the containment, the writing of a SOAR on Containment aspects of severe accident aerosols behaviour is recommended.

SESSION SUMMARIES

SESSION I: AEROSOL FORMATION, GROWTH AND TRANSPORT IN THE REACTOR COOLANT SYSTEM

Session Chairman: Jorma Jokiniemi (VTT, Finland)

SESSION I "Aerosol Formation; Growth and Transport in the Reactor Coolant System" included papers on aerosol formation by nucleation, a facility to study aerosol retention in a full scale CANDU reactor component, the IPSN programme on deposition in pipes as well as their SOPHAEROS code validation and a detailed modelling of particle deposition by thermophoresis in turbulent flows.

In the first paper, experimental and modelling results on CsOH particle formation in the presence of seeds and without seeds were presented. The results showed that seed particles affect the amount of vapour condensing on walls and the particle size. The modelling results demonstrated the importance of accurate multidimensional flow modelling even in a relatively simple system used in these experiments. The flow field was far from 1 D flow which is usually applied for aerosol modelling.

Current T-11 models are not capable of modelling complex flows that could take place in various parts of the RCS. In the general discussion after the session it was agreed that in this area there is a need to evaluate if the flow modelling in severe accident codes is sufficient.

In the second paper a facility to study aerosol deposition in CANDU reactor tube end-fittings was presented. The first tests with the system had been carried out and proved the set-up suitable for testing full scale components. To apply the results for plants more modelling and interpretation of mechanisms taking place are needed. Also experiments with different aerosol properties and flow conditions would be useful. In the general discussion it was pointed out that the deposition modelling in complex geometries lacks experimental data.

In the presentation by IPSN deposition in different Primary Circuit pipe systems were studied. Results from TRANSAT (turbulent deposition) and TUBA (thermo-phoresis and diffusiophoresis) programs were presented. TRANSAT experiments represented the T-H conditions expected in the RCS piping and no thermophoresis was studied due to the fact that Primary System pipes are insulated. TUBA experiments represented conditions expected in the SG tubes. Laminar flow was used in TUBA tests. From the comparison of experimental results and SOPHAEROS calculations it was concluded that there was sufficient agreement for most of the cases studied. Only tests where bend deposition was dominant gave disagreement between code results and measurements. The authors concluded that bend deposition modelling needs to be improved.

The SOPHAEROS code has been validated extensively against existing experimental data. As mentioned already deposition models were validated against TRANSAT and TUBA tests. The chemistry model was validated against Falcon experiments and resuspension against STORM experiments. Relatively good agreement for the chemistry was obtained, except for Iodine in the Falcon comparison.

In the last presentation of this session a detailed model on simultaneous eddy impaction and thermophoresis was presented. The temperature fluctuations caused by turbulence showed only minor effect on the total deposition velocity. The model results demonstrated the importance of turbulent eddies on thermophoretic deposition.

In the general discussion it was pointed out that the data on deposition in straight pipes is sufficient. However, the deposition/resuspension in by-pass sequences with very high flow rates (hundreds of meters per second) has not been studied. In this area more experimental data and understanding of deposition in compressible flows is needed. Currently no credit on deposition in safety analyses can be taken in these conditions. Also the fraction of vapours transported onto the walls, on existing particles and nucleated particles have importance on fission product transport in the RCS. In high flow rates resuspension becomes important and should be considered (this topic is discussed in Session 11).

The flow conditions in SGs during different accidents was also discussed. Conditions expected are from laminar to turbulent depending on the scenario. Thus it would be useful if the TUBA tests could be extended for turbulent conditions.

There was also general feeling that better flow modelling and coupling to aerosol behaviour could increase the accuracy of source term predictions.

There was no presentation on fission product chemistry in Primary Circuit, but this topic has become important as the PHEBUS results show that e.g., the chemistry of Cs and I is more complex than was expected. More data on this subject is needed for code validation.

SESSION II: AEROSOL RESUSPENSION AND REVAPORIZATION IN THE REACTOR COOLANT SYSTEM

Session Chairman: Denis Boulaud (IPSN, France)

In this session, six papers were presented. One concerns the revaporization of fission products in severe accident conditions and the five others the aerosol resuspension in the reactor coolant system.

The first paper presented by Auvinen *et al*. deals with the possibility of revaporization of fission products, due to the decay heat of the radionuclides, occurring at a later stage of an accident. To study these revaporization phenomena VTT Energy has constructed a thermal-gradient tube facility to determine the fission product vaporization rate by using synthetic radiolabelled samples. The test facility has proven successful in measuring the temperature dependence of CsOH revaporization. The vaporization starts at approximately 500° C and increases with temperature. The experimental results were compared successfully with, on one hand a numerical simulation calculated with the FLUENT CFD-software, and on the other hand with a simple engineering calculation. The practical interest of this device is that it can be adapted to study the revaporization rate of representative samples like those collected in the PHEBUS tests (FPT I for instance).

The second and the third papers concern the STORM project (Simplified Tests On Resuspension Mechanisms).

The presentation of Kuhn *et al*. deals with the new developments related to measurements of particle size distribution, mass concentrations and evolution of the deposit in the test pipe. A special emphasis is on the assessment of the overall measurement accuracy of all the instruments. Afterwards, some typical experimental results are given to prove their reliability. This paper shows the importance of advanced aerosol measurement techniques in experimental projects like STORM.

The paper of Hummel et al contains an up-dated description of the STORM-project. The emphasis is on the presentation of the tests performed and the most important data, including also a critical comparison and discussion of the results. One of the main lessons learned in this project is that resuspension depends strongly on the deposition mechanism.

The three last papers concern the modelling of aerosol resuspension or/and aerosol adhesion to surfaces. Broadly speaking, if one can consider that the current understanding of deposition mechanism is generally judged to be adequate, however the importance of mechanical resuspension of deposited particles from the surfaces is not yet established.

The paper by Parozzi et al describes a semi-empirical approach which seems to appear to the authors more suitable for severe accident applications. To set up such semi-empirical model the authors have identified a group of physical parameters which seems responsible for the resuspension phenomenon. This model which was implemented in the ECART code has the capability to be applied to multi-layered and multi-component aerosol deposits. In particular, the authors claim to formulate a more representative formulation for the adhesion forces by using a more representative value of the coefficient H for the intermolecular attraction coming from the STORM tests.

The paper by Hontanon *et al*. concerns the effect of roughness on particle adhesion to surfaces. The authors present a new model of particle adhesion to surfaces which accounts for the effect of surface roughness. For instance, the calculated adhesion force between SnO_2 particles and a rough surface was three orders of magnitude smaller than the adhesion force for a smooth surface. This new adhesion model has been implemented in the CAESAR computer code which simulates particle resuspension in turbulent pipe flows. The prediction, of CAESAR has been compared with the experimental results of the experiment SRI I of the STORM programme. CAESAR reproduces reasonably well the particle resuspension behaviour observed in the experiment SRI 1. This new model can be used to evaluate the particle-to-surface adhesion energy and force in the current models of particle resuspension based on either the energy balance or the force balance principles.

The last paper of this session by Friess and Yadigoroglu discusses various effects characteristic of the resuspension of multilayer deposits. A comparison between the PARESS experiments and the STORM experiments indicates that the PARESS deposits were easier to resuspend. The authors interpret this effect by the hypotheses that the PARESS deposits were more porous than the STORM deposits and generalise the model by Fromentin to include the bed porosity as an additional input param eter.

Discussion

The discussion has started by asking the importance of both mechanisms (revaporization and resuspension) to assess the source term to the environment. There were some indications, from plant calculations, that resuspension and revaporization could have a major impact on the source to the containment.

Afterwards, the question has risen of the necessity of further developments on the modelling of resuspension by semi-empirical and mechanistic approaches. Participants felt that both ways are necessary to identify important parameters like surface roughness, bed porosity, chemistry on the surface, stickiness of the particles.

Concerning experiments, at this date, there was not a clear demand to develop new generic experiments on resuspension. The feeling of participants is that the databases, furnished by the previous and current experiments, such as PARESS and STORM, is very good and well documented to develop and validate models. The needs correspond more to the development of specific experiments related to accident sequences clearly identified.

The situation is different to describe revaporization process and at this date only one experimental program is in progress in Finland. So, the need of new developments, both theoretical arid experimental, appears more clearly in order to understand the revaporization process.

SESSION III: COMPARISON OF REACTOR COOLANT SYSTEM CODES WITH EXPERIMENTS

Session Chairman: Alan V. Jones (CEC/JRC, Ispra)

This was the last session devoted to the circuit, and was intended to move in the direction of plant applications, following the more analytical experiments and theoretical papers of the first two sessions. Six papers presented and analysed results from the STORM and WAVE facilities and from the in-pile integral experimental programmes BTF and PHEBUS-FP.

The first STORM paper was a preliminary presentation of the results of ISP-40, looking at both deposition and resuspension phases with tin dioxide particles. Almost all participants calculated the flow one-dimensionally. Calculated deposits were uniform along the pipe and built up linearly, while the test data showed deposits tailing off towards the downstream end of the pipe and accumulating rapidly at first and then more slowly. The reasons for the observed behaviour are not known as yet. There were large differences in the predicted deposition, mostly caused by the inclusion or omission of resuspension simultaneous with deposition or poor choice of thermophoretic model coefficients, but several submissions came rather close to the measured total mass.

The resuspension phase was performed in a series of rising steps of flow rate, and participants were asked to calculate the suspended mass at each step. Various classes of model were employed, from very simple to sophisticated. The more mechanistic models predicted the qualitative behaviour, but none of the participants succeeded in coming close to the experimental results as a whole. The sizes of the resuspended particles were systematically underestimated, perhaps because no models took account of the formation of agglomerates in the deposit layer.

A second STORM paper looked at the deposition phase of all the STORM tests performed so far. Calculations suggest that even in the tests with pipe insulation present the dominant deposition mechanism was thermophoresis. STORM particles were too small for impaction to play more than a minor role. The thermophoresis models and their coefficients differ between the various codes compared in the paper but for the STORM deposition tests without insulation deposited masses are similar. With insulation the codes tend to overestimate the thermophoretic deposition.

The third paper introduced a facility, WAVE (JAERI), in which low-speed air flows transport a dilute CsI aerosol through a bend and sections of straight piping at high temperatures (1000 K). CFD calculations predicted rather simple one-dimensional flow patterns in most configurations, and a simple piping aerosol transport code reproduced observed deposits well. The case where the 4" outlet pipe pointed upwards produced much higher deposits, however, which were ascribed to the more complex recirculating flow predicted by CFD.

The fourth paper presented the BTF test series in general and the test BTF-4 in particular, concentrating on the reconstruction of the release curves using VICTORIA and back-calculation from gamma-spectroscopy measurements. To explain the observed deposition and the lack of revaporisation it was necessary to posit that cesium was present as the uranate. This brings out the need for species measurements e.g., by PTA. One cannot obtain enough information for code validation from spectrometry alone.

The last two paper presented some results from the first two tests in the integral degradation, release, transport and chemistry experiments PHEBUS FP as well as comparisons with code calculations. The data are not fully cross-checked, and only a limited range of conditions has been investigated so far.

Concerning releases one may mention the relatively high observed release of Te, Mo and Ru in the oxidising conditions of the tests, the dominance of silver, urania and other non-FP in the source, and the sensitivity of releases to the degradation stages of the bundle (surface area effect?). In the circuit the relatively low (10 - 20 per cent) deposition in the steam generator tube with strong wall-gas temperature difference and the observed mobility of deposits were notable features, and there was considerable discussion of the result that, with the exception of iodine, all elements were in aerosol form at 700° C. There is little direct speciation information so far to suggest an explanation. At the circuit outlet (150° C) a non-zero fraction of the iodine was in volatile form, which was also unexpected.

In the containment vessel (under relatively dry conditions) near-identical settling behaviour was observed for all elements, and diffusiophoretic deposition also appeared not to discriminate among elements. When washed into the sump iodine was seen to settle on the side walls and bottom. The formation of insoluble silver salts is proposed as an explanation.

Analytical results for PHEBUS FP indicate that the effect of irradiation in enhancing release is overestimated by commonly used models, and that they fail to account for the effect of changing geometries. Steam generator deposition was overestimated (factor 3). Complex circuit speciation, changing with time, was predicted by codes like VICTORIA or SOPHAEROS, but there was only indirect evidence for the predictions. Aerosol removal rates in the containment were quite well predicted by all codes, if the correct source (including size distribution) was taken as input. The well-mixed assumption appeared adequate for modelling.

Discussion

The discussion began by asking whether the results of the experiments made to date, including those of the session, were sufficiently well understood. It was agreed that in the absence of chemical effects deposition in pipes is now in this category. Resuspension was definitely not, and there were some indications from plant calculations that it could have a major impact on the source to the containment. Revaporisation was also felt to be significant but not understood well enough for plant calculations.

Other phenomena mentioned as needing more experimental and analytical investigation to reach the goal of sufficient understanding included processes in the upper plenum, processes in complex components, and source dependence. The PHEBUS tests are expected to provide input on this last point (including the effect of boron carbide control material on the chemistry and transport processes), while for upper plenum processes there was consensus that the impact on the source composition (rather than on the aerosol size distribution) was the key point.

For all of these topics participants felt that a well-considered programme of separate-effect tests offered the best hope for progress, to supplement the large-scale test programmes in progress or being terminated. There was strong interest in obtaining more chemistry information about deposits, but more engineering data such as measurements of the stickiness of particles for resuspension modelling would be very helpful.

SESSION IV: AEROSOL GROWTH, TRANSPORT AND DEPOSITION IN THE CONTAINMENT

Session Chairman: Abdelouahab Dehbi (PSI, Switzerland)

In Session IV titled: Aerosol Growth and Transport in the Containment, four presentations are given, three of which deals with experiments on aerosol growth and retention, and one describes a model for droplet removal from a two-phase flashing jet impacting on structures.

In the first paper, a summary is given on the KAEVER experiments which were performed between 1991 and 1997. The objective of the tests is to provide a database on the behaviour of soluble (CsI, CsOH) and insoluble (Ag, $Sn0_2$) aerosols in a variety of thermal-hydraulic conditions. A differentiation in the removal depletion rates is observed for individual aerosols and mixtures. For all types of aerosol, it is found that the depletion rates increase with humidity. In superheated atmospheres, the soluble aerosols and insoluble aerosols behave similarly. In condensing atmospheres, aerosol depletion is more pronounced for soluble aerosols. A mixture of Ag and CsI produces the surprising result that the depletion rates in slightly superheated atmospheres are smaller than those measured for individual components, implying a chemical reaction between the aerosols. The phenomenon is not reproduced when CsOH is used instead of CsI.

The second paper by AECL presents experiments on droplet characterisation in a two-phase jet which is expected to be formed when a high pressure primary liquid water is discharged in the containment. The experimental facility uses a commissioned PDA optical system to describe the droplets (size, velocity) in the flashing jet. The results show that the droplet size distribution is of a log-normal type. The geometric diameter increases first due to agglomeration and then decreases away from the nozzle. Axial velocities decrease monotonically with distance from the jet.

The third paper by AECL presents a model for the removal of water droplets from a flashing jet impacting on a plate. The model is based on four sub-models dealing with jet flashing, jet expansion, jet deflection and jet impingement, respectively. The model underpredicts somewhat the scarce data available, possibly because it does not simulate all the removal mechanisms present in the experiments. However, it correctly predicts that a large fraction of the droplets are removed upon impaction on the plate.

The last paper by NUPEC and Toshiba presents results of experiments dealing with fission product trapping in the leakage paths of the containment. Three series of tests are conducted to study the containment integrity under accident management, the failure temperature, and the fission product retention along the leakage paths, respectively. No leakage is detected under Japanese accident management conditions of 200° C containment temperature and twice the design pressure. Beyond these conditions, a small leakage is observed at temperatures above 280° C. Fission product decontamination factors of 10 to 1 000 are observed along the leakage paths depending on the type of penetration studied.

In the general discussion, it was agreed that the current modelling of aerosol growth in the containment seems appropriate provided the aerosol characterisation and thermal-hydraulic conditions are known with a good degree of accuracy.

More clarification is needed in the area of aerosol mixtures depletion to determine to what extent chemistry needs to be taken into account.

Knowledge of fission product retention in containment leakage is adequate for the types of paths looked at (small electrical penetrations, flanges). Additional work is needed to assess the leakage and retention through other types of paths such as containment cracks.

SESSION V: COMPARISON OF CONTAINMENT CODES TO EXPERIMENTS

Session Chairman: Esther Hontanon (CIEMAT, Spain)

The session consisted of two papers. The first paper showed the results of a simulation with CONTAIN and FIPLOC of one experiment performed at the VICTORIA facility of IVO[1] (Finland). In the experiment, the dome, ice-condenser compartments and lower rooms were mixed by natural circulation, while stagnation was observed in the central rooms. The atmosphere of the dome and lower rooms was saturated, and the atmosphere of the central region was superheated (RH>80 per cent) during the entire experiment. Despite of the great accuracy in the predicting thermal-hydraulics, the behaviour of the CsOH aerosols predicted with the two codes diverged significantly. FIPLOC predicted reasonably well the build-up of the airborne CsOH concentration, whereas CONTAIN largely overestimated the concentration of CsOH in the atmosphere. In the decay phase FIPLOC predicted much larger aerosol depletion rates than observed in the test, whereas the depletion rates estimated with CONTAIN agreed fairly well with the experimental ones. In the FIPLOC calculation, the option of instantaneous equilibrium droplet size was used. In the CONTAIN calculation, however, droplet growth was calculated dynamically. In FIPLOC, a dynamic growth option is also available.

The second paper dealt with the COCOSYS computer code under development at GRS (Germany). COCOSYS is a containment code system, which models thermal-hydraulics, aerosol physics, hydrogen combustion, recombiners, pool scrubbing, iodine chemistry, fission product decay and other phenomena. COCOSYS calculates thermal non-equilibrium between the atmosphere and the pool within each cell. In the simulation with COCOSYS and FIPLOC of the experiment VANAM M3, atmospheric humidities were more accurately predicted with COCOSYS (non-equilibrium) than with FIPLOC (equilibrium). COCOSYS has been applied to the analysis of a ND* sequence in a German plant. The calculations were done in dry conditions. The results showed the effect of thermal-hydraulics on aerosol distribution and depletion in the containment. Higher airborne concentrations and larger aerosol decay rates were found in the rooms mixed by natural circulation than in the isolated ones.

Discussion

There is general consensus about the experimental database on containment aerosol behaviour, which is considered to be sufficient and well qualified. It covers a wide range of prototypical accident scenarios in terms of geometrical configurations, atmospheric conditions and aerosol species. Uncertainties in both thermal-hydraulic and aerosol measurements have been largely reduced in the last years because of the use of much improved instrumentation. However, one of the conclusions of the ISP-37 exercise was that the accuracy of the thermal-hydraulic measurements is not sufficient with respect to the needs of aerosol modelling and code assessment.

The database on aerosol properties such as particle shape factors, density and collision efficiencies is very scarce. The general opinion is that aerosol properties may play a role in dry atmospheres and can be neglected in wet atmospheres, for which the spherical approach is sufficiently accurate.

A code benchmark on a series of AHMED experiments concluded that steam condensation onto aerosols is adequately modelled for a mono-compartment vessel in stationary and well-defined thermal-hydraulic conditions. However, the ISP-37 exercise showed that steam condensation onto

1. Now Fortum Engineering Ltd.

aerosols in multi-compartment geometries and unsteady thermal-hydraulic conditions is not satisfactorily modelled. Further research is needed to improve the accuracy of the thermal-hydraulic predictions and the modelling of atmosphere-aerosol coupling.

With respect to the applicability of containment codes to plant scenarios, the general opinion is that aerosol behaviour in dry conditions provides a satisfactory upper bound of the aerosol source from the containment. Sensitivity analyses are recommended to assess the uncertainty in the source term predictions due to the uncertainty in the particle shape factors. Aerosol behaviour in wet conditions may significantly reduce the aerosol source from the containment, However, the uncertainties in modelling aerosol behaviour in condensing atmospheres are so large (orders of magnitude in airborne concentrations) that predictions of the steam condensation models are not reliable enough for source term evaluation purposes.

Phenomena such as boiling pools, fast containment depressurization or hydrogen combustion may promote the resuspension of the aerosols deposited on the containment walls and sumps in the late stages of a severe accident. The aerosol sources resulting from these phenomena are quite uncertain and have not been systematically investigated up to date. The presence of large amounts of water in the containment may result in the revolatilization of iodine species both dissolved and suspended in the water. Moreover, at the high temperatures attained in the containment in case of hydrogen burn, aerosols of caesium iodide (CsI) convert to gaseous iodine (I_2). The safety significance of CsI to I_2 conversion is unclear. The general feeling is that it may be of interest to investigate this phenomenon, but the priority is not high.

SESSION VI: INTERACTION WITH SAFETY FEATURES INSTALLED IN THE CONTAINMENT

Session Chairman: Hans-Josef Allelein (GRS, Germany)

In Session VI entitled ‘Interaction with Safety Features Installed in the Containment’ we heard four presentations about the aerosol behaviour in a condenser, as well as about experimental as analytical work performed to understand the influence of a containment spray system on aerosol wash out.

The first one from PSI dealt with a Passive Containment Cooling System. In addition to remove decay heat the heat exchangers remove a fraction of aerosols. Most of the aerosol particles impact on the upper plenum surfaces and are then entrained with the condensate water towards the lower plenum. We learnt in the discussion that the experimental results are strongly influenced by the species of aerosol. One of the main issues addressed in this test series is the interaction between the aerosol deposition and the flow field in the condenser upper plenum. Simulations with a CFD tool confirm qualitatively that most of the aerosol particles impact on the upper plenum surfaces. It seems to me that this is a further example for the need to know the thermal-hydraulics with high precision for the adequate simulation of the aerosol behaviour.

The second paper provides two models improved by NUPEC and their validation. In one of these models the collision factors of agglomerated aerosols are derived by the single type integration of the collision kernel. With this method the developers try to secure numerical accuracy for the calculation of all the types of aerosol collisions, on one hand and to achieve fast running capacity for PSA studies with MELCOR on the other one. Furthermore, models for the removal of gaseous iodine were incorporated into MELCOR. This led to good agreement between MELCOR calculations and the results of one CSE experiment. One participant suggested that modelling of removal of gaseous iodine by sprays was not needed, because the iodine is aerosol in containment under severe accident conditions. The further discussion raised the question about the necessity of simulating the gaseous iodine removal by sprays without finding a final answer.

The third and fourth papers presenting IPSN and NUPEC efforts showed us two different approaches to come to an understanding of the interaction between containment spray systems and aerosols. IPSN presented the test facility CARAIDAS, designed and built in order to determine the collection efficiency of aerosols and iodine absorption by drops under representative conditions for steam condensation or evaporation in a post accident atmosphere. In the ACACIA model steam condensation, aerosol collection and iodine absorption are coupled. The variation of the drops during their fall is considered. The basic assumption in the model is that the monosized drops are independent. A good agreement between experimental collection efficiencies and ACACIA predictions for drops smaller than 400 µm was found, while the difference was significant for larger diameters.

In contrary to this detailed approach NUPEC carried out an integral test series to provide the data for demonstrating the effective aerosol removal by containment spray and for validation the MELCOR code after modifying its aerosol collection by diffusiophoresis. MELCOR results agreed as well in aerosol concentration transient as in pressure transient with the experimental ones. The Japanese facility has a height of 18 m, while the French one is five m high. In both of the experiments CsI is used as aerosol material.

The detailed experimental approach is as well necessary as the integral one to come to a deeper understanding of the influence of a containment spray system on aerosol wash out and its adequate modelling. Furthermore there was general agreement that CsI used in experimental tests seems to be appropriate because it is a well-known aerosol. Particle density and particle size are identified as most essential properties to characterise the aerosols interacting with spray droplets. In a further step the importance of the interaction between droplets should be examined with respect to its value for assessing spray system performance.

SESSION VII: POOL SCRUBBING AND RE-ENTRAINMENT IN CONTAINMENT

Session Chairman: Grant W. Koroll (AECL, Canada)

Session VII addressed the topics of aerosol retention by pool scrubbing and of aerosol generation (or resuspension) by pool boiling and bubbling. This session also included discussion of the paper of K. Fisher, presented in Session V, but relevant to this session.

The first paper described the Poseidon II experiment, measuring scrubbing in hot pools. The decontamination factor (DF) was observed to increase with height of the pool and carrier gas steam fraction. The BUSCA code was found to be non-conservative in predicting DF at the extreme heights. The reason given for BUSCA under-predicting the DF at extreme heights is that the hydrodynamic model used (bubbly flow) overestimates residence times. A chum turbulence model was proposed as a possibly more appropriate alternative.

The second paper described the REVENT program to quantify re-entrainment in boiling pools. The experiment examined soluble and insoluble substances and had steady state capability. Re-entrainment at the surface of the pool was found to depend on the concentration of fission product simulant and on gas velocity.

The third paper described an analytical study of mechanisms for droplet formation at bubbling water pool surfaces. These processes are a weak but long-lasting source of fission products relevant in the late phase of an accident where fission products are accumulated in the pool. The mechanisms of droplet formation (film droplets, jet droplets and chum flow droplets) depend on gas flux through the pool. The fast-running code RECOM simulates the processes as well as the mechanistic code RESUS. Surface tension effects from suspended and dissolved material were discussed as an important factor in real plant application.

Conclusions:

Pool scrubbing models contain uncertainties which are linked with uneven detail of modelling. Some physical processes are modelled in detail, while models for plant behaviour remain quite simple. Uncertainties in pool scrubbing models require systematic review, in terms of the relative importance of different processes and tolerance for uncertainty in plant application.

Re-entrainment experimentation and modelling at bubbling liquid pools need to consider non-ideal (i.e., contaminated) liquids.

SESSION VIII: PLANT APPLICATIONS

Session Chairman: Jason H. Schaperow (NRC, USA)

The first paper describes an effort in progress to evaluate key uncertainties associated with aerosol behaviour in predicting source terms from severe accidents. This effort involves calculating source terms for eight reactors for a total of 20 sequences. One preliminary result is that an important phenomenon for some sequences is the deposition of aerosols in the primary circuit which forms the basis for a revaporisation source term. With regard to the importance of deposition mechanisms in the reactor coolant system, one participant stated that gravitational settling is the most important, followed by thermophoresis, and then turbulence. Questions were raised about the completeness of the study and the importance of combustion on release of iodine.

The second paper presents a study of the effect of diffusiophoresis and resuspension in the reactor coolant system and containment. The study involved estimating releases to the environment for different assumptions for boundary conditions, such as diffusiophoresis retention factors for the reactor coolant system. In the area of re-entrainment, the study concluded that mechanical resuspension does not appear to give rise to substantial re-entrainment affecting the atmospheric source term.

One participant stated that revaporisation is caused by steam heating of the pipe and that heating from deposited fission products is a small effect. Another participant noted that the high flow rates following fission product deposition needed for resuspension have not been seen in any of his thermal-hydraulic results. One participant noted that there is a large database and little uncertainty in the area of deposition enhanced by condensation on pipe walls.

The third paper describes a comparison of fission product deposition results from MAAP3.0B and VICTORIA92 at the end of the in-vessel phase of a TMLB' scenario. The additional detail in the fission product models in VICTORIA had a minor effect on the deposition results. Both codes predicted that settling was the main fission product retention mechanism with half of the fission products depositing in the upper plenum.

One participant stated his calculated showed a significant amount of deposition due to thermophoresis in the beginning of the tubes, because the temperature difference between the vapour and the wall could be high. Another participant disagreed because his thermal-hydraulic results showed no possibility of maintaining more than a small temperature difference in this area. Additional discussion focused on the modelling of the melt progression and the thermal-hydraulic conditions by MAAP3.0B and the impact on fission product deposition in the reactor coolant system.

The fourth paper examines the effect of the number of condensed phases modelled on aerosol behaviour during a temperature-induced steam generator tube rupture sequence. The VICTORIA code was used for this analysis. one calculation was run assuming one homogeneously-mixed condensed phase. Another calculation was run using three immiscible condensed phases, one of oxides, one of metals, and one of iodines. The dominant aerosol deposition mechanisms were the same in both calculations; however, deposition occurred further downstream when three condensed phases were modelled because of the higher iodine volatility. The net result was that offsite fission product releases were the same in both calculations.

The fifth paper describes an evaluation of hygroscopic aerosol behaviour in the AP-600 containment using MELCOR 1.8.4. Several sensitivity cases were run, including cases with and without containment sprays and cases with and without hygroscopic growth of aerosols. The results showed that hygroscopic growth could result in a significant reduction in the amount of radioactive aerosol suspended in the containment atmosphere. One participant asked what humidities were seen in the MELCOR 3BE sequence for AP-600. The question was answered by another participant, who stated that calculations he had seen for AP-600 sequences showed relative humidities in the range of 50 to 60 per cent. One participant stated CsI is not very hygroscopic at relative humidities lower than 90 per cent.

The sixth paper presents two new design applications of natural deposition modelling. In the first application, settling, diffusiophoresis and thermophoresis in the containment are modelled to show acceptable fission product releases to the environment for licensing AP-600. In this application, the results show that each of these three mechanisms contribute equally to reduction of offsite release for AP-600, which uses an externally cooled steel shell containment. In the second application, three additional mechanisms are modelled for fission product deposition in a steam generator tube rupture sequence, namely turbulent deposition in the broken tube, deposition by high speed flow out of the broken tube across the outside of the other tubes (impaction), and thermophoresis onto the outside of the tubes reducing the release by a factor of 30. One participant asked whether the probability of rebounds of particles was considered when calculating DF’s for flow across steam generator tubes. The presenter explained how his calculations implicitly accounted for rebounds. There was some disagreement with the explanation.

The seventh and final paper of this session discusses plant calculations for fission product transport during the in-vessel phase for VVER-reactors. Analyses was performed with SOPHAEROS using MARCH and CATHARE thermal-hydraulic results as input. Analyses were also performed with MELCOR for comparison. One conclusion of the study was that to get significant deposition in a large break LOCA scenario, the flow path must include the steam generator tubes where settling is the dominant deposition mechanism. Another conclusion was that modelling the fission product release from the fuel as always aerosol instead of initially vapour that transforms into aerosol had little impact on fission product behaviour. The participants discussed the appropriateness of and the types of comparisons between detailed codes and integral codes that would be worthwhile and what could be learned from such comparisons.

APPENDIX

MEMBERS OF THE PROGRAMME COMMITTEE

Dr. Hans-Josef ALLELEIN (GRS, Germany) - Chairman

Professor Denis BOULAUD (IPSN, France)

Mr. Salih GÜNTAY (PSI, Switzerland) (replaced at the meeting by Dr. Abdelouahab DEHBI)

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Dr. Jorma JOKINIEMI (VTT, Finland)

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Mr. Charles G. TINKLER (NRC, United States) (replaced at the meeting by Mr. J. SCHAPEROW)

Dr. Jacques ROYEN (OECD/NEA) - Secretary