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Workshop on

AEROSOL BEHAVIOUR AND THERMAL-HYDRAULICS IN THE CONTAINMENT

Fontenay-aux-Roses (France)
26-28 November 1990

Organised by

OECD NUCLEAR ENERGY AGENCY

in collaboration with

COMMISSION OF THE EUROPEAN COMMUNITIES

and

COMMISSARIAT A L'ENERGIE ATOMIQUE

TECHNICAL SUMMARY

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS
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TECHNICAL SUMMARY

OF THE WORKSHOP ON

AEROSOL BEHAVIOUR AND THERMAL-HYDRAULICS

IN THE CONTAINMENT

held at

Fontenay-aux-Roses, France; 26th-28th November 1990

Prepared by

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FOREWORD

The Workshop on Aerosol Behaviour and Thermal-Hydraulics in the Containment held at Fontenay-aux-Roses, France from 26th to 28th November 1990 was sponsored by the Committee on the Safety of Nuclear Installations (CSNI) of the OECD Nuclear Energy Agency. It was organised in collaboration with the Commission of the European Communities and the Commissariat à l'Energie Atomique.

The Workshop was the third meeting in the series of CSNI specialist workshops in this area.

The meeting held at Karlsruhe in 1984 had identified the topics of coupling between thermal-hydraulics and aerosol behaviour, chemical aspects of nuclear aerosols, and validation of modelling codes against large-scale experiments as being of main importance for continuing attention.

There was good coverage of all of these topics at the Brussels Workshop, held in collaboration with the CEC in 1987, demonstrating substantial advances, and reconfirming their importance. At that time the LACE and DEMONA series of experiments had given direct evidence of the importance of coupling of aerosol behaviour to thermal-hydraulics, and of chemical effects such as hygroscopicity. These large-scale tests had also demonstrated that a number of important modelling problems still existed.

Substantial progress had been made since the Brussels Workshop, and the Marviken-V/DEMONA/LACE workshop organised in 1988. It is now recognized that the thermal-hydraulic and aerosol phenomena are in some instances tightly coupled, and codes have been developed to solve the corresponding equation sets simultaneously. CSNI therefore considered it appropriate to review and discuss the results of this work, the progress made, the programmes, the chief objectives being to reduce uncertainties in aerosol behaviour, and to identify difficulties and problems outstanding.

CEA's Institut de Protection et de Sûreté Nucléaire (IPSN) kindly offered to host the Workshop. Let them find here the manifestation of our thankfulness, in particular Mr. M. Livolant, Mr. J. Duco, and Dr. M. Réocreux who acted as General Chairman of the Meeting. CEA also published the proceedings of the Workshop (CSNI Report No. 176); these were prepared with speed and skill by Mrs. F. Pickaerts and Miss Ch. Tiquet, under the direction of Mrs. F. Duhamel.

We also wish to express our gratitude to the Programme Committee who organised the scientific programme of the meeting: Dr. P. Clough (AEA Technology/SRD, UK), Mr. E. Della Loggia (CEC), Dr. I Dunbar (AEA Technology/SRD,UK), Dr. J. Gauvain (CEA/IPSN), Dr. J. Jokiniemi (VTT, Finland), Dr. E. Schrödl (GRS, Germany). Special thanks are due to the Technical Chairman of the Workshop, Dr. P.N. Smith (AEA Technology/Winfrith, UK), who put together the following Technical Summary on the outcome and the main conclusions of the Workshop, with the untiring assistance of the Programme Committee and the Session Chairmen. The Technical Summary has been endorsed by the Committee on the Safety of Nuclear Installations and CSNI's Principal Working Group on the Confinement of Accidental Radioactive Releases (PWG4).

J. Royen
CSNI Secretariat

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SUMMARY CONCLUSIONS AND RECOMMENDATIONS

This workshop follows on from two previous joint CEC/CSNI workshops: the first held in Karlsruhe in 1984; the second held in Brussels in 1987. The present workshop focussed upon thermal-hydraulics and their coupling to aerosol behaviour (a topic identified as important in the previous two workshops). Within the above constraints the papers covered a wide range of topics. Old experiments were revisited, new experiments reported and proposals for future experiments were discussed. Analyses were reported using well established codes, new developments to codes were presented, and new codes were revealed; in addition new modelling was discussed which may need to be incorporated in the codes in the future. A number of presentations were devoted to international code comparison exercises, both past and present, and possible future exercise were suggested. Each of the above topics is discussed in more detail below, starting with the experiments on which much of the modelling is based and against which the codes are validated.

The workshop was well attended, with 48 delegates representing 13 countries; 26 technical papers were presented. This gives some indication of the continuing high level of interest in the topic of aerosol modelling and its coupling to thermal-hydraulics.

1. EXPERIMENTAL PRESENTATIONS

1.1 Previously Completed Experimental Programmes

The Marviken, DEMONA and LACE programmes along with accompanying support programmes and calculational exercises were all completed some years ago and a joint workshop had been held in Montreux since the Brussels workshop. Between them the three programmes provide a wealth of data for code validation and to guide development. Initial comparison with calculation had been poor in many cases; this had resulted in numerous improvements to the codes which lead to much better agreement, though even now, not all of the relevant code development has been carried out. The experiments had given rise to many conclusions, only a few of which are mentioned here. In the absence of radiolysis and agents such as boric acid transport was found to be by aerosol. Pipe retention was found to be important and to depend strongly upon the chemical and physical form of the materials being transported. Pipe bends were also found to play a significant role in pipe retention. All insoluble aerosol species used were seen to behave the same, however, soluble aerosols could behave very differently. The importance of solubility was emphasised by the high removal rates which soluble species could achieve relative to their insoluble counterparts. Furthermore it was noted that soluble species are washed off walls by condensate runoff, which would cause relocation of decay heating in a reactor accident. The need for good thermal-hydraulics predictions in order to produce sensible aerosol calculations was demonstrated.

1.2 Current Experimental Programmes

A series of experiments to investigate the important processes involved in pipe deposition was reported. The results indicate that model development is required for pipe deposition of hygroscopic materials. these experiments should be considered in conjunction with the LACE tests and the experiments of others, such as Wright, Fromentin and Bowsher.

Separate effects tests are underway which seem to confirm the existence of gravitational agglomeration and may eventually allow estimates of the gravitational collisional efficiency to be obtained.

Several series of essentially separate effects tests are underway in the PITEAS facility to investigate condensation onto walls and onto hygroscopic aerosols, diffusiophoresis and agglomeration. Preliminary results are available on first three of the above topics; these seem to validate to diffusiopheresis model in the AEROSOLS B2 code (based upon the Schmidt-Waldmann equation) and indicate that the equilibrium approach to modelling condensation onto hygroscopic aerosols is adequate for moderate saturations (up to 95% saturation was used). Thermal-hydraulic and aerosol calculations are being performed using the JERICHO and AEROSOLS B2 codes, respectively, both before and after each experiment, which is to be strongly commended.

Interaction between experiments and theoreticians is also an important aspect of the small scale integral experiments being performed in the Falcon facility. The experiments model the whole sequence of events, starting with fuel meltdown and release processes, followed by pipe transport and retention and ending with containment behaviour. The main focus of the tests is chemical speciation which has provided a stimulus for much theoretical analysis of both thermochemical and aerosol behaviour. Heterogeneous particles have been observed in the tests and analysed. Different materials have been found to transport differently, especially control rod and fuel materials. Transport of caesium to the containment was found to increase in the presence of boric acid, thus confirming the importance of boric acid to fission product transport. Some results suggest that iodine transport may not be solely by aerosol when boric acid is present. Some evidence has been found for cadmium iodide.

Two new series of experiments for the Battelle Model Containment were outlined. The VANAM series is already underway and consists of multi-cell thermal-hydraulic and aerosol experiments with particular emphasis upon local fog formation. The second series of experiments is designed to study hydrogen combustion in chains of connected cells;

particular attention will be devoted to the effects of igniters and recombiners.

2. CODE/MODEL APPLICATION

2.1 Application To Previously Completed Experimental Series

The Kelvin effect had been included in the ART code which was then applied to a number of the NSPP tests. Agreement was found to be better than that reported with older versions of the CONTAIN code which did not include the Kelvin effect. However, there remained significant dissagreement with the shape of the aerosol decay curves for the infamous 504 and 505 tests.

Since the LACE tests LA-2 and LA-4 had shown the importance of hygroscopicity to containment aerosol behaviour the NAUA code has been developed to include soluble aerosols. The resulting code, NAUA-HYGROS has been applied to the LA-2 and LA-4 experiments and shows much improved agreement with experiment. However, the difference in behaviour between the hygroscopic caesium hydroxide particles and the insoluble manganese oxide particles could not be fully predicted; this is a limitation of the current generation of 1-D aerosol codes. The solute modelling in the MAAP code is much simplified compared to NAUA-HYGROS and comparison of the two codes showed that the MAAP model can be non-conservative with respect to NAUA-HYGROS by an order of magnitude. Calculations with the REMOVAL-2H code for test LA-2 also showed much better agreement with the hygroscopic model. Calculations using an earlier version of the CONTAIN code, with no modelling of the solute effect, also confirmed the impossibility of obtaining anything like reasonable agreement with the LACE experiments using only insoluble aerosol models; this further reinforces the need for solute modelling in aerosol codes.

There was a review of the many and varied approaches to the calculation of heat and mass transfer to walls. Those applicable to reactor accident codes include: coupled kinetic theory and Nusselt theory; mass transfer analogies with Nusselt Theory; heat transfer correlations, in particular the many variants of the Uchida correlation. The main problem with the kinetic theory approach is to determine the boundary conditions at of order a mean free path from the wall. Caution was also urged when implementing the Uchida correlation to make sure that the version being used is that one appropriate to the conditions which the model is to address. Though different models could give rise to significantly different heat transfer coefficients, when applied to LACE test LA-4 is was found that they all gave rise to similar thermal-hydraulics predictions (though subsequent work casts some doubt on the latter conclusion). Developments to the models for heat and mass transfer in the CONTAIN code were reported. Implementation of the modelling proposed by clement at the Brussels meeting surprisingly made little difference. However, modification of the driving force for convection in the Grashoff number (to allow for the fact that it is usually dominated by the gas composition difference across the boundary layer rather than the temperature difference) resulted in considerable changes to the predicted relative humidity. The same was also true of a correction to the thermal radiation modelling to allow for the temperature drop between the first node of a structure and the interface between the gas and the water film. Neither modification produced a noticeable difference to the predicted values of the other thermal-hydraulic parameters but the effect upon airborne condensation could be large. The changes had resulted in improved agreement between calculated and measured values of airborne condensation in the DEMONA B3 experiment.

Comparison of calculation with measurement for the coupled multi-cell thermal-hydraulic and aerosol experiment, DEMONA A9, had shown the need to model temperature gradients in water pools. However, most codes had not been modified to allow for such temperature distributions at the time of the workshop.

2.2 Application To Current Experimental Programmes And Code Comparison Exercises

FIPLOC code calculations had been compared with the results of the first test (M1) in the current series of multi-cell thermal-hydraulic and aerosol transport experiments in the Battelle Model Containment, VANAM. Predicted aerosol transport and local fog formation were found to be in reasonable agreement with the experimental measurements.

A CEC code comparison exercise was reported to be underway, based upon the buoyancy driven circulation experiment, F2, in the Battelle model Containment. Difficulties were being experienced by the modellers as a result of the difficulty in accurately determining the rather large leak rate of the containment. In addition the energy extracted from the atmosphere by the application of the camera coolers over the extended period of the experiment had turned out to be a major contributor to the energy balance in the test. The observed atmospheric stratification during the heatup phase of the test had proved difficult to model using lumped parameter codes and the specified 11-cell nodalisation. In addition there were probably localised plumes and counter current flows in some flowpaths which were not taken into account in any of the analyses. There appeared to be problems with water film runoff in some calculations and in some of the initial calculations insufficient care had been taken to ensure that stable solutions had been obtained (such effects can easily be missed if the results are plotted on an even multiple of the timestep and the period of the oscillations is twice the timestep leading to only the peaks or troughs of the oscillations being plotted).

A number of HDR tests have been used as ISP's. In particular the blowdown phase of test T31.5 was used as a DBA ISP. Later in the test hydrogen was introduced. Code predictions failed to model plume effects and predicted too great a penetration of hydrogen into the lower compartments. The light gas distribution test, E11.2, was first used as the focus of a blind calculational exercise organised by PHDR. Subsequently an open ISP was based upon the experiment, which was underway at the time of the workshop. Once again the degree of thermal and compositional stratification in the containment had been seriously underestimated by the codes. Lessons had also been learned by the experimenters, in particular the prolonged operation of the instrument cooling lines had contributed significantly to the energy balance in the same way as the camera coolers had in the Battelle Model Containment (their effect had been negligible in previous tests of much shorter duration).

Proposals were also made for future code comparison exercises. The successful experience with VANAM test M1 led the project to propose a joint thermal-hydraulic and aerosol benchmark exercise based upon VANAM test M2. Another joint thermal-hydraulic and aerosol benchmark, but for a single-cell geometry was proposed involving the ITHACA code. The ITHACA aerosol code systematically solves the coupled atmosphere thermodynamic and aerosol equations simultaneously; a code comparison exercise would therefore allow other code users and developers to assess whether or not the looser coupling in their codes provides adequate accuracy for their purposes.

2.3 Application To Future Experiments

A report was given on the second CEC calculational exercise on the Phebus experiments. Phase A, had consisted of plant calculations designed to establish the kind of conditions that should be aimed for in the experiments. The Phase B calculations reported at the workshop were aimed at determining whether or not these conditions would be achieved during the experiments. The calculations had confirmed that the proposed time acceleration was indeed required in order to counter the excessive heat removal resulting from the thick steel containment vessel. Scaling estimates indicated that the containment should be reduced in volume from 25 m^2 to 10 m^2 and that the water pool in the containment was too large to achieve a realistic dose rate. Similarly it was predicted that there would be too much hydrogen in the tests and that the exaggerated wall surface area would lead to the deposited fission products being too thinly spread. Since the study many major changes to the experiments had been proposed which overcome many of the problems revealed by the calculations. Most notably the containment size had been reduced and it was proposed to heat the steel vessel to prevent aerosol deposition and alleviate the excessive heat transfer. This will be complemented by an active cooling device of smaller dimensions onto which condensation and aerosol deposition will occur. Further interest was generated by CONTEMP calculations which demonstrated how useful Latin hypercube sampling can be for sensitivity studies.

2.4 Plant Calculations

CONTAIN calculations were presented for a DCH sequence and a long-term overpressurisation sequence in the Surry plant. In the long-term overpressurisation calculation most of the pressure rise resulted from the boiling of sump water arising from wall runoff. Igniting hydrogen before high pressure melt ejection was shown to greatly reduce the pressure rise due to DCH. A demonstration was given that coarsening the nodalisation of the containment can considerably alter the timing of predicted hydrogen combustion resulting in lessoning of the predicted consequences (eg delaying predicted containment failure until long after the aerosol had deposited). A further set of CONTAIN calculations for an ice-condenser experiment had resulted in reasonable predictions of the decontamination factor. In addition counter current flow had successfully been predicted in the diffuser. However, the degree of thermal stratification had been under predicted.

THALES/ART calculations for a Mark II BWR had shown that early containment failure (before release from the fuel has occured) leads to the highest releases. Containment failure some time after core melt was shown to give decontamination factors of two orders of magnitude or so, due to aerosol settling (though the source term was found to be sensitive to containment failure location).

Multi-cell FIPLOC calculations indicated that fog formation (local, atmospheric condensation) was sensitive to stratification of the atmosphere and to the amount of water holdup on walls. Multi-cell calculations tended to predict more condensation than their single-cell counterparts and stratification further increased the amount of airborne condensation.

A methodology was presented for producing conservative estimates of aerosol removal during DBA's. When containment sprays and/or fancoolers are operating condensation is necessarily massive. Estimates of diffusiophoretic removal are then essentially independent of a particle size distribution (so long as the particles are not too small) and can be used to give conservative estimates of particle deposition.

3. CODE/MODEL DEVELOPMENT

The Canadian INTARES system was presented (and demonstrated during coffee and lunch breaks). The concept is similar to the CEC's

ESTER programme, which will allow many codes to be run in parallel in order to produce a whole accident calculation from a set of codes each of which can individually only model part of the accident sequence. This interesting concept may eventually be able to effectively extend the ESTER capability to all OECD member states.

The newly developed ITHACA code was written to solve the coupled atmosphere thermodynamic and aerosol equations strictly simultaneously. The code uses steam tables to provide steam properties. Calculations with the code show strong coupling between agglomeration and condensation, indicating that simplified models need to be treated with care. The calculations also confirm that using uncoupled codes results in non-conservative predictions, as the lack of feedback from the latent heat of condensation results in massive overprediction of airborne condensation in uncoupled codes. Plant calculations are required in order to confirm the importance of the strong coupling in accident conditions. Unfortunately the code is too slow running for realistic accident sequence calculations; more efficient methods may therefore need to be developed, with the use of a moving grid for the condensation calculation appearing to offer the greatest potential speed up.

The effects of electrostatic charging of aerosols had been reconsidered. A criterion had been developed to determine when charging effects were important (compared to brownian agglomeration). For the effects to be important the airborne particle concentration must be less than a critical value. It was shown that it can be non-conservative to neglect electrostatic charging; the need for experiments with radioactive aerosols was therefore stressed.

4. FUTURE DIRECTIONS

It is clear from the number, quality and diversity of papers presented at the workshop that considerable progress has been made in the understanding of phenomena of importance in severe reactor accidents since the previous meeting in Brussels. Much of the progress had resulted from, or benefited from, international collaboration and close co-operation between experimenters and theorists; such trends are to be much encouraged.

A great wealth of data has been produced by experimenters, especially over the last decade or so. Unfortunately computer codes have not always been modified in line with the improved understanding that has resulted from the experiments: pool temperature gradients observed to be important in DEMONA A9 are not modelled in most codes at present; it is disappointing that only the ITHACA, CONTAIN and FIPLOC codes seem to have attempted to couple their thermal-hydraulic and aerosol models as indicated in the LACE experiments; generalisation of aerosol codes to multiple dimensions in order to predict the independant behaviour of soluble and insoluble particles, as observed in LACE, has not yet been attempted; pipe deposition models in primary circuit codes require further development, especially for hygroscopic materials. In some cases, such as the coupling of aerosol and thermal-hydraulic models the importanance to plant calculations has been demonstrated (in this case at the Brussels workshop). Other developments, such as multi-dimensional aerosol codes, need careful justification at reactor plant scale, which remains outstanding. It is high time that such issues be resolved and accident codes modified accordingly. Codes should then be reapplied to experiments such as NSPP, Marviken, DEMONA and LACE in order to demonstrate that the modifications adequately account for the original discrepancies. Though the databases for the above tests are well kept it would be prudent to complete such an exercise before the experimenters who executed the original tests have all retired!

There has been a definite trend towards multi-volume experiments in recent years. This has lead to much improved understanding of inhomogeneous phenomena in reactor containments. It remains to explain the consistent underprediction of atmosphere stratification by the computer codes, which could have significant implications for estimates of the effect of gas combustion in containments. Inhomogeneous phenomena such as atmospheric stratification, plume effects and counter-current flow in single flowpaths appear to be of great importance and have not been treated properly in recent calculations. An approach to the successful treatment of such phenomena needs to be developed. Multi-volume experiments and modelling have shown the need to pay greater attention to detail than in many of their single cell forunners; in particular, experimenters need to take greater care in accounting for all mass and energy sources and sinks in their tests and much more time needs to be given to the theoretical analysis of such experiments. Further experimentation and theoretical analysis are essential in this area and should necessarily go hand-in-hand.

The other direction gathering momentum is that of containment chemistry. The difference in transport of different chemical species has been demonstrated in small scale tests and is to be investigated at larger scale in the Phebus experiments. The coupling of chemistry models to coupled thermal-hydraulic and aerosol codes is essential if the data from such tests are to be analysed and the results extrapolated to reactor plant scale. Results presented at the workshop emphasised the need to develop appropriate nucleation models if such phenomena are to be predicted. It was also made clear that experiments with radioactive aerosols will be necessary in order to complete the picture, a goal which will, hopefully, be achieved by the Phebus-FP experiments.

The progress made to date in understanding the phenomena of relevance to severe reactor accidents is indeed impressive. The summary conclusions of the Brussels workshop in 1987 serve as a reference point against which this progress can be judged. Seven important aspects of aerosol modelling were identified there and of these significant further progress can be claimed in six areas, namely: code validation; basic theory; thermal-hydraulic coupling; flowing systems; understanding sources of uncertainty; treatment of chemical and compositional effects, particularly solubility, along with some progress in defining the chemical nature of the material released into the containment. The final topic, non-mechanistic aerosol models, has received little further attention, though evidence of problems in treating steam condensation in such models was presented. Despite the progress some phenomena require further investigation and the coupling of all of the relevant phenomena is not yet complete. Though a substantial amount of work remains to be done, the point appears to have been reached at which, with proper international collaboration, the relevant understanding and modelling should be achieved in the foreseeable future.

22 August 1991

Annex

O E C D

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

Pursuant to article 1 of the Convention, the OECD shall promote policies designed:

-- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and this to contribute to the development of the world economy;

-- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and

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

The current Signatories of the Convention are Australia, Austria, Belgium, Canada, Denmark, Finland, France, the Federal Republic of Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States.

N E A

The OECD Nuclear Energy Agency (NEA) now groups all the European Member countries of OECD and Australia, Canada, Japan and the United States. The Commission of the European Communities takes part in the work of the Agency.

The primary objectives of NEA are to promote co-operation between its Member governments on the safety and regulatory aspects of nuclear development, and on assessing the future role of nuclear energy as a contributor to economic progress.

NEA works in close collaboration with the International Atomic Energy Agency, 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 scientists and engineers. It was set up in 1973 to develop and coordinate the activities of the OECD Nuclear Energy Agency concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations. The Committee's purpose is to foster international co-operation in nuclear safety amongst the OECD Member countries.