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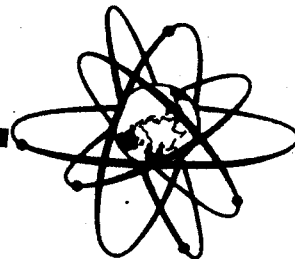
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STATUS OF DIRECT CONTAINMENT HEATING
in CSNI Member Countries

Report of Task Group on Ex-Vessel Thermal-Hydraulics

MARCH 1989



COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS
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REPORT
OF
TASK GROUP ON EX-VESSEL THERMAL-HYDRAULICS

STATUS OF DIRECT CONTAINMENT HEATING IN
CSNI MEMBER COUNTRIES

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ABSTRACT

The status of activities on direct containment heating in the light water reactor programs in OECD/CSNI countries is presented. Experimental and analytical studies are reviewed. Approaches or measures are discussed for accident management in relation to direct containment heating. A discussion is given of common and diverging views among the countries based, in part, on responses to a questionnaire. The key issues are discussed and recommendations are provided for future CSNI work on direct containment heating.

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I INTRODUCTION

For hypothetical LWR severe accident sequences in which the reactor system remains pressurized during core meltdown it has been estimated that certain modes of vessel failure could lead to a high pressure ejection of molten core material, followed by blowdown of system gases. In the case of a local failure of the lower head the molten materials would initially be ejected into the cavity beneath the pressure vessel but may subsequently be swept out of the cavity into the containment atmosphere where the liberation of thermal and chemical energy (oxidation of debris) can directly heat the atmosphere. This complicated physical and chemical process is known as direct containment heating (DCH) and may be a significant source of containment pressurization. This may imply early failure of the containment building with an enhanced radiological source term, due to the production of radioactive aerosols.

The current focus of DCH studies has been on the pressurized water reactor design and accordingly this is the main focus of this report. However, DCH concerns for the boiling water reactor design have been noted in some countries and studies are being initiated or planned.

The objectives of this report are to:

- i) summarize the status of the DCH issue in CSNI member countries, and highlight areas of common understanding;
- ii) review areas of existing research, that may be primarily aimed at particular plants, but may have results of wider interest;
- iii) discuss possibilities for preventing or mitigating the consequences of DCH;
- iv) identify areas of special interest to be discussed in the Task Group.

This report was written to provide the various CSNI member countries with "state-of-the-art" information on direct con-

tainment heating. It is intended that this information should be helpful to those countries in determining whether DCH is relevant to their reactors and what information currently exists on the subject.

II PHYSICAL PROCESSES AND PHENOMENA RELATED TO DCH

The initial conditions for DCH are determined by the in-vessel processes and phenomena during core meltdown. The actual DCH phenomena are ex-vessel processes. These are discussed in Section II.1 and II.2 respectively, with greater emphasis placed on the ex-vessel aspects.

II.1 In-Vessel Processes and Phenomena

In the case of a severe accident sequence, leading to reactor pressure vessel (RPV) failure under high system pressure, such as that expected for a small break loss of coolant accident or a station blackout, DCH is of concern. In addition to the system pressure, the failure mode of the RPV and the melt conditions in the lower plenum, of the RPV prior to its failure, may have a great influence on the extent of DCH. These conditions are determined by the process of core degradation, mass slumping into the lower plenum, quenching of hot material by the residual water and details of the structural design of the RPV bottom. A large number of different physical processes, phenomena and structural design parameters determine the initial conditions for DCH /23/. Some of the key points will be described in more detail below.

II.1.1 Specific In-vessel Phenomena

Metal-water reaction

The extent of the exothermic reaction of steam mainly with zircaloy will be controlled by the temperature level of the core materials, the local availability of steam together with the accessibility of unoxidized metallic surfaces containing zirconium. A high degree of oxidation leads to a high energy release into the core region resulting in an acceleration of the core degradation. In addition, the degree of oxidation determines the type of debris formation and the melting temperature of oxidized and metallic materials, the quantity of unoxidized metal in the melt at the time of vessel failure and the amount of pre-existing hydrogen at vessel-failure time.

Thus, the extent of oxidation influences the initial conditions of DCH, as an important parameter.

Natural convection

Natural convection of gases in the RPV and the connected piping leads to a transport of energy from the core region to colder structures of the system. In addition the gas flow carries some steam from the system to the core region thus increasing the oxidation rate of zircaloy. While the transport of energy from the core reduces the temperature rise in the core, the enhanced zircaloy-steam reaction leads to the opposite effect. According to the present knowledge, the effect of natural convection results, at least, in a higher degree of zircaloy-oxidation, an extension of the time span for core degradation and heat-up of different structures of the primary system.

Core slumping

The initial slumping of molten materials from the core region into the lower plenum of the RPV could result in high steam production rates due to the quenching of hot material in the residual water in the vessel. This will lead to an acceleration of the melting process because of the increased exothermic reaction between zircaloy and steam in the core region. The mass flowrate of molten materials into the lower plenum is of major importance. A short term slump of molten materials will lead to different melt or debris conditions prior to vessel failure, than would be expected in case of an extended core slumping process.

Failure mode of the RPV

After an evaporation of residual water, solidified materials in the lower plenum will heat up again by decay heating to the melting point. There might be also the possibility, that molten material penetrate water without complete break up and subsequently evaporation of only limited amount of water would occur. As a result, the RPV lower structures, being covered by

solidified and/or molten materials, will be heated up. Due to high system pressure and temperature loads, the vessel will fail.

Structural details of the RPV and of connecting pipework determine the failure mode of the primary system under pressure. Current work on DCH assumes a local failure in the bottom part of the vessel. Penetrations in the lower part of the RPV, such as core instrumentation nozzles, are assumed to fail first, leading to a limited opening for the discharge. A gross head failure mode, such as a ballooning-type is more likely to occur in a design of the bottom head without penetrations. Such a failure mode could severely damage the reactor cavity and the vessel support structure, with a subsequent dispersal of debris and steam causing a significant DCH. However, the main threat from this mode of failure comes from the likely vessel response. In particular, there is a probability that the vessel restraints could be sheared and the vessel projected against the containment wall causing an early containment failure.

If the piping, especially from the vessel to the pressurizer, is heated by hot gas flows, a failure of the primary system, prior to RPV lower-head failure, may also be possible. This will lead to a system blowdown with some entrainment of hot particles from the partly molten core. Such failure modes of the system are still under investigation. Mode and timing of vessel-failure are very important to subsequent events.

Melt conditions

Mixing of molten materials takes place in the lower plenum prior to vessel failure. Of importance is the possible incorporation of significant quantities of steel into the melt. This affects the amount of chemical energy available in case of a DCH as well as general conditions of the melt. A longer time span between core slumping and vessel-failure implies a higher temperature of the melt and a larger mass in the lower plenum. Therefore for early vessel failure there will be less molten

materials on the bottom of the vessel at a lower temperature level.

II.1.2 Summary of Initial Conditions for DCH

To summarize, the main issues of importance for the possibility and extent of DCH are:

- i) system pressure prior to vessel failure;
- ii) mode of vessel (or system) failure;
- iii) mass of molten material in the lower plenum;
- iv) composition of the melt and gases in the system;
- v) temperature of the melt.

II.2 Ex-Vessel Processes and Phenomena

The extent of containment pressurization from DCH depends on a host of phenomena. These are discussed in detail below and are grouped into three phenomenological categories (discharge phenomena, cavity phenomena and containment phenomena) roughly in order of occurrence.

II.2.1 Discharge Phenomena

The discharge phenomenology associated with a local failure of the RPV, caused by expulsion of an instrument guide-tube, has been reasonably well established /1/. The important phenomena identified in this case are discussed below. However, a gross lower-head failure cannot be ruled out, especially for those reactors that do not have penetrations in the lower-head. (see section II.1; failure mode of RPV)

Effervescence and jet breakup

Effervescence caused by the rapid release of dissolved gases from the debris would lead to expansion and breakup of the discharging jet. This process has been observed in the "SPIT"

experiments using iron/alumina thermite and nitrogen overgas /2/ and has been studied analytically by Frid /3/. It is believed that hydrogen would be dissolved in the debris in the reactor situation.

Gas blowthrough and pneumatic atomization

The onset of gas discharge (gas blowthrough) can occur whilst a significant fraction of the debris remains in the vessel even if the hole is close to the centre of the lower-head. Therefore a significant fraction of the debris can be expelled during a two-phase discharge period. The two-phase discharge will cause pneumatic atomization of the debris; hence a change in the particle size distribution. However, most of the debris, apart from the fine aerosol cloud which represents a small fraction of total discharge, is likely to undergo deposition and re-entrainment within the cavity. Therefore, the initial size distribution may be important only for the source term (i.e. aerosol production) and not for the loading from DCH. Gas blowthrough may mark the beginning of rapid oxidation of the melt, hence production of hydrogen. However, the magnitude of hydrogen production at the orifice has not yet been assessed.

Hole ablation

The vessel hole size can be greatly increased by ablation of the steel vessel wall. Hole ablation is therefore an important phenomenon since the hole size controls the duration and intensity of the gas discharge into the cavity. The simple model used in /1/ agrees well with observations in the HIPS experiments /4/, but there are uncertainties in applying the model to the reactor case in which the geometry and materials are different. In particular, the formation of UO_2 crusts and their effectiveness in reducing ablation is a major uncertainty.

Effect of in-vessel water

The effect of simultaneous or sequential discharge of water and debris have not been studied experimentally therefore it is possible only to speculate on the likely phenomena. These could include rapid steam production in the jet causing enhanced breakup and dispersal, or quenching of the debris which could reduce chemical reaction. The short discharge time for the debris (a few seconds) implies that water is unlikely to enter the vessel during this phase. However, water which enters the vessel and is expelled during the gas discharge e.g. from the accumulators may interact with debris in and around the cavity.

II.2.2 Cavity Phenomena

The phenomenology has been reasonably well established only for "open" PWR cavities which consist of a cylindrical region beneath the vessel connected to a tunnel region, with one or more large openings into the lower containment. The cavity tunnel, which houses the instrument guide-tubes, is regarded as the main route for debris dispersal, although some dispersal may occur via an annular gap around the RPV. No experiments have been performed to establish the important phenomena for the "closed" PWR cavities associated with reactor types without lower-head instrument penetrations. The only route for debris dispersal from some closed cavities is via the annular gap around the vessel.

Entrainment of debris within the cavity

With the onset of gas discharge into an "open" PWR cavity the debris deposited onto the cavity floor will be swept along to the end of the horizontal tunnel region from where it becomes entrained as particulate in the gas flow. This sequence has been observed in hydrodynamic dispersal experiments /5, 6/. For a sufficiently high pressure discharge all of the debris is rapidly entrained from the cavity floor. In this case the important parameter is the size of the entrained particles. The

entrainment threshold and entrainment rate become more important in relatively low pressure sequences when entrainment may be incomplete.

Complex gas flow

Experiments /6, 7/ show that the gas flow through the cavity can be very non-uniform and that the flow is greatly affected by the position of the hole in the lower-head and by the presence of cavity structures. The non-uniformity leads to locally high flowrates which can cause early onset of entrainment and significantly greater can entrainment rate. This effect could be particularly important for the issue of defining a "low pressure cut-off" for DCH. The ability of structures to withstand the melt ejection could be an important issue for those designs in which structures strongly effect the gas flow, hence entrainment.

Deposition and re-entrainment at bends

When the flow encounters the many bends in and around the cavity, many of the larger particles will be deposited onto the walls. However, experiments /8/ show that much of the deposited material may be rapidly re-entrained by splashing or other mechanisms. This process is of great importance as it will strongly influence the amount and the size distribution of the debris reaching the main containment volume.

Trapping of debris by freezing onto surfaces

Some of the debris could be retained within the cavity or its surroundings by the process of freezing onto surfaces. This would prevent the debris from giving up all of its energy to the containment atmosphere. Experiments /4/ suggest that freezing onto concrete surfaces may be inhibited; hence the presence of an exposed steel liner and steel structures in some cavities may be significant.

Separation of the debris from the steam flow

Some of the debris may become separated from the main steam flow by entering a cavity sump or some other compartment eg through doorways in the side of the cavity which exist in some plant designs (Sweden). Where this possibility exists then a portion of the debris may be removed from the initial inventory of discharged material without interacting appreciably with the containment atmosphere or the discharging steam.

Dispersal via the annulus around the RPV

An alternative route for debris dispersal in PWR plants is the annular gap around the vessel which leads into the containment via clearance gaps around the primary system pipes. This route could contribute significantly to dispersal particularly if the cavity becomes highly pressurized. In some cavity designs this path represents the only route for debris to reach the containment atmosphere. In the HIPS 8C experiment, at Sandia National Laboratories, there was extensive dispersal via an annular path around the melt generator. However, there were no obstructions or additional flow restrictions included in this experiment.

Oxidation by steam within the cavity

A major contribution to the pressurisation, predicted to result from DCH, is caused by the exothermic oxidation of iron and zirconium in the debris. Oxidation in steam is much less exothermic than in oxygen, but produces hydrogen that can later recombine with oxygen in the containment to release the additional energy. Scoping calculations /9/ indicate a potential for significant containment pressurisation resulting from hydrogen burning in the containment. These calculations are highly idealised and much further work is planned to make more realistic estimates of this apparent threat.

Rapid heating and pressurization of the cavity

Entrained debris in the cavity presents a large area for heat-transfer to the gas. The heat-transfer can very rapidly raise the temperature of the gas to that of the debris. This process has two main consequences; firstly, it increases the gas velocity hence the entrainment rate and secondly may lead to local pressurization of the cavity. Pressurization of the cavity may lead to structural damage and possibly missile production. This is of particular concern for closed cavity designs.

Interactions with water in the cavity

Some cavities may be deliberately or unavoidably filled (or partly filled) with water at the time of vessel failure. The presence of water may lead to the occurrence of a number of phenomena including:

- (i) steam explosion or steam spike;
(This could lead to a very high cavity pressure especially if there is sufficient water to prevent rapid venting of the cavity. Water slugs and other possible missiles must be considered.)
- (ii) quenching of debris;
(This could mitigate DCH by providing an alternative heat sink and by preventing complete chemical reaction.)
- (iii) increased dispersal and oxidation caused by an additional steam source;
(This may be particularly important for relatively low pressure discharges.)

The effect of water in the cavity is a major outstanding issue which is being addressed in the ongoing research programs in the US and UK.

II.2.3 Containment Phenomena

There are a large number of containment designs encompassing major differences in configurations, size and special operating and design features. In the discussion below the applicability of the various phenomena to particular types of containment is noted.

Rapid heat-transfer from the dispersed debris

The sensible and latent heat-transfer from the debris is expected to be the major contributor to local or global pressurisation of the containment during DCH. Two of the important parameters for the heat-transfer efficiency are the particle size distribution and the residence time for debris in the atmosphere. Both of these parameters will depend strongly on the behaviour of debris as it impacts surfaces in the containment. The U.S. has an ongoing research program to study debris/structure interactions. Another possible limitation to the heating of the atmosphere is the "cloud effect", for which the particle density may be so great that oxygen cannot readily diffuse into the cloud and radiative heat transfer to the atmosphere could be greatly reduced.

Rapid oxidation of dispersed debris

Finely fragmented dispersed debris provides a large area for oxidation. The exothermic oxidation of iron and zirconium in an oxygen rich atmosphere can provide a substantial contribution to the total energy release during DCH. The contribution would be much less for an inerted atmosphere in which only steam from the blowdown and evaporation of cooling water is available to cause oxidation.

The particle size distribution and the residence time are important for oxidation efficiency as they are for heat-transfer discussed above. Other important issues are the possible mitigative effects of solid state reaction rate limits and local oxygen/steam starvation in an inhomogeneous containment atmosphere.

Transport and burning of hydrogen

Hydrogen can be produced by the oxidation of iron and zirconium in the steam rich lower containment compartments and may subsequently be transported into regions containing sufficient oxygen to allow burning of hydrogen to occur. This process has the potential to cause substantial containment pressurisation without requiring debris dispersal into the main containment volume. Heating of the atmosphere by dispersed debris may reduce the effectiveness of steam to inert hydrogen combustion. The load due to burning of hydrogen is clearly not possible for inerted containments, but may be of great importance for ice condenser containments in which the debris and steam may be removed by the condenser to leave a highly flammable hydrogen/air atmosphere.

Heat-transfer to structures

Impact of debris onto containment surfaces may be an important contribution to reducing the "worst case" pressures by transferring energy directly to structures and by reducing the surface area for debris-to-atmosphere heat transfer. Heat-transfer from the atmosphere to structures may play an important role, particularly if there is a significant delay between the initial pressurisation from DCH and the burning of hydrogen produced during DCH.

III REVIEW OF CURRENT RESEARCH

This section reviews experimental and analytical investigations of ex-vessel phenomena directly related to DCH.

III.1 Experimental Investigations

III.1.1 Experiments Using High Temperature Melts

SPIT/HIPS Tests

The SPIT and HIPS tests /4, 8, 10/ were performed by Sandia National Laboratories under sponsorship from the USNRC. The main objective of the SPIT tests was to develop and characterize a reliable melt ejection system. There were nineteen tests in the series, some of which involved discharge into open vessels containing water. Only the last two tests (SPIT 18 and 19) involved discharge into scaled reactor cavities (1/20 scale models of Zion). The HIPS tests followed on from the SPIT series and concentrated on dispersal from the cavity using a 1/10 scale model of the Zion cavity. There were eight tests in the HIPS series; two with water filled cavities.

The simulated melt ejection in both HIPS and SPIT experiments was achieved by burning an iron-oxide/aluminium thermite in a small steel vessel (melt generator) that was pressurized with either nitrogen or carbon dioxide. The heat of the reaction melted a brass plug in the bottom of the melt generator to allow the 10 kg (SPIT) or 80 kg (HIPS) of molton thermite to be ejected. Pressures in the range 3.3 MPa to 11 MPa were used for the discharge.

The main observations and results of the SPIT and HIPS experiments were:

- (i) jet divergence and breakup;
(This effect was greatest when the more soluble nitrogen gas was used; hence effervescence is

believed to be a major contributor to jet breakup).

- (ii) ablation of the hole;
- (iii) aerosol production;
(The fraction of the discharged mass in the form of particles with diameter less than $10\mu\text{m}$ was estimated to be 1 to 6 %).
- (iv) nearly complete dispersal from the model cavities;
(Retention in the concrete cavity models was about 1 to 5 %. Retention in the alumina cavity (SPIT 18) was significantly higher (about 42%) due to freezing onto surfaces. Outgassing of the concrete is believed to prevent stable crusts forming on concrete surfaces).
- (v) dispersal of debris mainly as particulate (log-normal distribution with mass mean diameter ~ 0.5 - 1.00 mm)
- (vi) violent interactions or explosions in water filled cavities;
(Dispersal and pressurization data is limited because both the water filled model cavities were destroyed).
- (vii) low debris retention by ex-cavity concrete structure;
(Although debris droplets impacted the structure positioned at the cavity exit in HIPS 7C /8/, they were almost completely re-entrained and dispersed).
- (viii) dispersal via an open annulus around the melt generator;
(HIPS 8C confirmed this postulated dispersal route by demonstrating that the dispersal fraction via the annulus was approximately equal to the flow area fraction (about 1/3) out of the cavity).

SURTSEY - DCH experiments

The SURTSEY-DCH experiments are a continuation of Sandia's experimental program sponsored by the USNRC. The experiments are based on the HIPS discharge and cavity apparatus, but include a large (approximately 100 m³) steel vessel representing a scaled large dry containment. The intention, with the current test matrix, is to independently vary the initial conditions and geometrical configurations in order to quantify their effects on DCH and aerosol production. Preliminary results show substantial pressurization of the SURTSEY vessel and also show the importance of debris impact onto steel surfaces.

The proposed variations in test conditions are:

- (i) thermite mass (20 kg, 80 kg);
- (ii) debris impact onto steel vessel wall;
- (iii) inert atmosphere;
- (iv) steam, air and hydrogen atmosphere;
- (v) cavity geometry (Surry rather than Zion);
- (vi) steam driving gas;
- (vii) melt composition (in particular, including metallic zirconium);
- (viii) water drops in the atmosphere;
- (ix) water in the cavity.

CWTI experiments

The corium/water thermal interaction (CWTI) tests, /11/, were performed by Argonne National Laboratories under sponsorship from EPRI. The experimental apparatus is broadly similar to that employed in the HIPS/SURTSEY experiments at Sandia. However the following important differences should be noted;

- (i) the cavity is 1/30 scale and is not a geometrically accurate model of any existing plant;

- (ii) an uranium based melt was used (UO_2 , ZrO_2 , steel);
- (iii) the cavity, connecting paths and containment vessel had large areas of exposed steel (the HIPS cavity is concrete).

The driving gas pressure was varied from 0.4 MPa to 5 MPa.

The CWTI experiments show:

- (i) lower dispersal than HIPS (typically 30 to 80 % retention in the cavity);
- (ii) very little "containment" pressurisation from DCH;
- (iii) water in the cavity increases dispersal because of rapid steam production.

The high retention of debris is attributed to freezing onto the steel cavity surfaces. However, it should be noted that this effect may be greatly reduced at a larger scale for which the surface to volume ratio is less. Also, it should be noted that the thermite used in these tests had very little superheat. The DCH efficiency is low because of a short debris path-length before deposition and trapping onto steel surfaces in the containment.

III.1.2 Hydrodynamic Dispersal Experiments

A number of small scale hydrodynamic dispersal experiments have been, or are currently being, supported by the US, UK and Sweden. The important features of these experiments are that:

- (i) they use room temperature fluids, hence do not include heat-transfer phenomena;
- (ii) they use transparent plastic cavity models which allow visual observation of the dispersal phenomena.

Argonne experiments

A series of dispersal experiments was performed at Argonne, under sponsorship from EPRI, using a 1/30 scale tubular cavity model /5/. The driving gas used was nitrogen; the debris simulants used were water, a liquid metal alloy (Cerrelow-136) and steel shot. The main objective of this study was to determine the flowrate threshold for entrainment and sweepout.

The results show that dispersal begins at approximately one half of the theoretically predicted entrainment threshold based on the average gas velocity in the cavity.

UK experiments

There is an ongoing experimental program at UKAEA, Winfrith, sponsored by the UK Department of Energy and the Central Electricity Generating Board to study dispersal for the proposed Sizewell B plant. The experiments are performed using a 1/25 scale accurate model of the Sizewell B cavity. The driving gases used are air and helium; the liquids used are water, silicone oils and Flutec PP9. The main results /6, 7/ are the observation of a highly non-uniform gas flow in the cavity and the importance of cavity structures in greatly reducing the dispersal rate. The non-uniform gas flow is believed to be the cause of the low entrainment threshold observed in these and in the Argonne experiments.

A similar series of experiments has been performed at Winfrith under sponsorship of the Swedish State Power Board, to study dispersal for the Ringhals 2, 3 and 4 plants. A low melting point Indium/Gallium/Tin alloy was used in these experiments. The results are not currently available. Additional simulant experiments at 1/100-scale and 1/25-scale are being performed by the Central Electricity Generating Board. The emphasis of this work is on flow mapping and particle size measurements.

Brookhaven experiments

There is an ongoing experimental program, /12/, at Brookhaven National Laboratories sponsored by the USNRC, to study dispersal in 3 different PWR cavity designs; namely Zion, Surry and Watts Bar. The cavity experiments are performed using 1/42 scale models. The driving gas is nitrogen; the liquids used are water and Wood's metal. The results show that there is very little retention of liquid in any of the model cavities during a scaled high pressure (7 MPa) blowdown. The experiments are currently being extended to include transport of dispersed material through a model of the lower containment of the Zion plant. Experiments are also underway to study dispersal at relatively low pressures.

Sandia Experiments

Experiments have recently begun at Sandia National Laboratories to study dispersal at relatively low pressures using low temperature simulants in a 1/10-scale Zion cavity. These tests will be compared with the high temperature experiments.

III.2 Analytical Modelling

III.2.1 Modelling of Discharge and Cavity Phenomena

Several computer codes are being developed to model discharge and cavity phenomena such as debris dispersal and steam/hydrogen production. These codes use simple, one-dimensional models of the discharge and cavity flows. Additional processes are treated either parametrically or by applying empirical correlations.

The EJECT module is being developed at Sandia, as the linking routine between MELPROG and CONTAIN for high pressure melt ejection accident calculations. EJECT calculates the discharge through a failure in the lower-head using the phenomenological models proposed by Pilch and Tarbell /1/.

A high pressure discharge and cavity model has been developed at the University of Wisconsin /13/. This model treats the discharge from the vessel, interactions of debris with water in the cavity and dispersal of debris and water from the cavity. The model has been used in conjunction with the containment code HECTR for DCH analysis.

A "stand-alone" code, CORDE, is being developed by the UKAEA /14/. The discharge model in CORDE is similar to EJECT. The multi-cell cavity model includes chemical and thermal energy transfer and empirical correlations for entrainment and deposition derived from the experiments at Winfrith. CORDE will be interfaced with CONTAIN to perform plant calculations in the UK.

Other similar computer codes have been written at Argonne /15/ and at Brookhaven National Laboratories /16/ as part of their combined experimental and analytical DCH programs.

III.2.2 Containment Modeling

Many calculations have been performed in the US and UK which give upper-bounds to DCH by assuming complete, adiabatic, equilibration of the dispersal debris with the containment atmosphere. The methodology of this approach is given by Pilch and Tarbell /17/. These calculations generally predict unacceptably high containment pressures if a large fraction of the core is dispersed.

Improved estimates of the pressurization have been obtained by including simple particle-to-gas heat-transfer and chemical reaction rate correlations in the CONTAIN code. The inclusion of some of the rate limiting processes reduces the degree of pessimism in the calculations, but very high pressures are still predicted in some cases /9/. It is possible that the well-mixed assumption in the CONTAIN code may lead to a significant over-estimate of the final pressure by failing to account for effects such as the local depletion of oxygen or

steam. Therefore, calculations have been performed at Sandia to assess the feasibility of using the three-dimensional, finite-difference spray modelling code KIVA /18/ to support CONTAIN calculations. A similar approach has been proposed by Brookhaven. They intend to use HMS /19/ to analyse complex flows in their small scale debris transport experiments.

IV ACCIDENT MANAGEMENT RELATED TO DCH

IV.1 Preventive Measures

Depressurisation of the primary system is the only measure that has so far been identified as a possible means of preventing DCH. Whilst some countries have, or intend to introduce, procedures involving depressurisation of the system, these measures are primarily aimed at reducing the probability of core melt /20/, and have not been introduced specifically to prevent DCH. These procedures include the use of high and low pressure bleed and feed. Alternative low pressure injection systems are proposed. Depressurisation is also being considered as a measure to mitigate the consequences of a possible gross head failure of the RPV in the case of core melt /21/ under high pressure.

Other countries (see Section V.1) are considering depressurisation of the system specifically to prevent DCH in the event of imminent core melt at high system pressure. The main issues associated with this action are:

- i) establishment of appropriate criteria for initiation of depressurization
- ii) adequacy of the systems designed to achieve depressurization.

It has to be checked for plant-specific systems, that it is possible to depressurize to a level, which would be effective in limiting debris dispersal.

The possible competing risks of depressurisation, hence loss of coolant inventory, must be considered in i). Depressurisation at an early stage of the accident could result in an early heat up of the core.

IV.2 Mitigative Measures

Mitigative measures related to DCH have received rather less attention than the preventive measure discussed in Section IV.1. Only some consideration and recognition has been given to mitigative approaches to DCH and it is therefore worthwhile to review the status of this subject.

There are three approaches to potential mitigation that have been identified by the authors of the report. They are:

1. Flooding of the reactor cavity with water;
2. Debris retention mechanisms or devices in the reactor cavity region;
3. Containment inerting.

A fourth potential approach to DCH mitigation could involve containment sprays. However, the advantages and disadvantages of such an approach have not been reported in the literature.

IV.2.1 Flooding of the Reactor Cavity

The presence of water in the reactor cavity may, under certain accident conditions, have beneficial mitigative effects on the course of the accident. The potential for quenching hot debris is well known from the earliest severe accident studies. Additionally, water may serve as a fission product scrubbing mechanism and thereby lead to a reduction in the source term to (and from) containment.

The flooding of the containment with water has been identified as a potential strategy for maintaining containment integrity in the Swedish program /22/ for mitigation of core melt conse-

quences. In this program, although DCH is not specifically mentioned, it is noted that the important counter-measure to pressure build-up that would lead to early failure of containment is injection of water into the containment by the containment spray system.

The efficacy of water in the reactor cavity as a mitigative measure is briefly discussed in Section VI.5. Current experiments and analysis do not provide conclusive evidence that water in the cavity would mitigate DCH. Williams et al /9/ studied the effect of co-dispersal of water with core debris on the peak pressure load in containment. They predict a broad maximum in the peak pressure load as a function mass of co-dispersed water. Finally, potential competing risks have been identified /23, 24/. These include: steam spikes, steam explosions, and enhanced metal-water reactions.

IV.2.2 Debris Retention Mechanisms or Devices

The ejection of core debris to the open regions of the containment gives rise, of course, to the direct containment loads that have caused the DCH scenario to be a concern for early containment failure. If a reactor cavity is effectively closed from the upper regions of containment or if significant structures exist within the cavity region (see Section V.1), then the dispersal of debris from the cavity region could be correspondingly limited. This suggests that obstructions which would inhibit debris dispersal could be placed in the regions near the cavities of reactors that otherwise offer little or no resistance to debris dispersal. Baffles and barriers have been informally discussed /24/ as well as gravel beds (perhaps Al_2O_3 gravel).

For new reactor designs, the Advanced Reactor Severe Accident Program /25/ of the U.S. Department of Energy explicitly recognizes mitigation of DCH by considering reactor cavity designs which would inhibit dispersal of debris.

Recent experiments by Tutu et al /32/ indicate that there is a broader range of cavity designs that are not retentive than had been initially anticipated.

While retention of debris in the cavity region would limit the direct thermal loads that would be produced by the presence of hot debris in the upper regions of containment, there exists the potential for enhanced interaction of the metallic component of the debris with steam (see section VI.2, but also note comment in section II.2.2) in the reactor cavity which would produce hydrogen that could subsequently burn in the upper regions of containment. The trade-offs between these competing threats to containment have not been evaluated. Similarly, retention of debris may enhance the potential for steam explosions and thus structural loading in the cavity region.

IV.2.3 Containment Inerting

The inerting of the containment atmosphere, as an accident management measure related to DCH, has received little discussion. The benefit from inerting would be to limit the potential for the burning of hydrogen with oxygen in the containment atmosphere. Boiling Water Reactors of the Mark I and Mark II designs in the U.S. as well as related designs in other OECD countries are inerted with nitrogen during normal operation. Therefore the hydrogen burning loads that can contribute to DCH would be suppressed under these conditions. However, these containments have relatively small volumes when compared to large dry PWR containments. Thus DCH thermal and mechanical loads to containment from hot, dispersed core debris and chemical energy generated in ex-vessel metal-steam reactions may pose significant threats to containment even without the additional threat of hydrogen combustion.

The efficacy of inerting other containment types (either during normal operation or in anticipation of high pressure melt ejection) has not been discussed in current accident management programs or plans. Calculations which compare DCH in inerted, large dry containments with the non-inerted case will be presented shortly /33/.

V. STATUS IN CSNI COUNTRIES

To obtain a survey of the status of DCH in different member countries of CSNI, a questionnaire was prepared by the authors of this report (see appendix A). In addition, the authors have made use of national position papers on DCH that had previously been submitted to the Task Group by USA, UK, France and Italy. The main objective was to obtain information on:

- i) different views on the relevance of DCH to safety;
- ii) research work on this issue in different countries.

V.1 Responses to the Questionnaire

The evaluation of the questionnaire is shown in table 1. It should be noted that questions no. 3, 4 and 6 are summarized in one column. Question no. 2 has been omitted because all the answers given are related to PWR-systems. Only FRG, Netherlands and USA stated that the possibility of DCH in a BWR will be investigated in future.

The answers given to question no. 5 (second column) cover theoretical or experimental work, which could be used either to fix initial conditions for high-pressure melt ejection or to give a basis to exclude DCH (e.g. failure mode of primary system prior to vessel melt through).

The responses given to the questionnaire provide a good survey of the status of DCH and different views on the subject.

Table 1:
Evaluation of DCH-Questionnaire

Member Country	Status of DCH	DCH addressed in Safety Assessments?	Basis for Initial and Boundary Conditions	Investigations of Ex-Vessel Phenomena	Preventive or Mitigative Actions	Key Cavity Design Features
		(1), see note 3)	(5)	(3); (4); (6)	(7)	(8)
France	no		1. CATHARE 2. PHEBUS	none	H2-procedure installed ("feed and bleed", partially depressurized)	Narrow, closed no sump water flooding
Germany	Possibility only		1. ATHLET-SA, STCP 2. CORA, NIELS	none	Depressurisation of the system planned mainly to prevent core melt	Narrow, closed no sump water
Italy	no		1. MAAP, STCP	none	Depressurisation of the system planned to prevent core melt.	Open with tunnel, flooding possible
Netherlands	yes		1. RELAP5-SCDAP (planned) 2. Chemical reactions (planned)		Consideration of rapid system depressurization	Narrow, closed no sump water flooding
Sweden	yes		1. MAAP, STCP 1. Modelling of separate effects (jet-behaviour of molten mat.) 2. Core debris dispersion in 1/25 scale of cavities		Consideration of rapid primary system depressurisation.	Open, door ways and partially sloping floor

Notes 1) theoretical work
2) experimental work
3) number of questionnaire, see appendix A

Table I (continued):
Evaluation of DCH-Questionnaire

Member of Country	Status of DCH Safety Assessments?	DCH, addressed in Initial Boundary Conditions	Basis for Initial and Boundary Conditions	Investigations of Ex-Vessel Phenomena	Preventive or Mitigative Actions	Key Cavity Design Features
	(1), see note 3)	(5)	(3); (4); (6);	(7)	(8)	
Switzerland	no	-	none	Consideration of rapid system depressurization	not known	
U.K.	yes	1. Core melt progression and natural circulation (MELPROG and FLOW-3D) Initial cond. for DCH from bounding assumptions and calculations.	1. Code development (CORDE) 2. Debris dispersal in 1/25-scale cavity model (collaboration with U.S. experimental/theoretical programs)	Rapid system depressurization may be considered	Open cavity with cable tunnel. Possible flooding in some scenarios	
U.S.A.	NUREG-1150; NUREG-1265; IDCOR-85.2	Programs on core melt progressions and natural circulation; see NUREG-1265, chapt. 2 and 3	Experimental and analytical investigations at several laboratories; see Section III	Consideration of rapid system depressurization	Fourteen cavity designs identified in IDCOR-85.2 ranging from "open" to "closed"	

1) theoretical work
2) experimental work
3) number of questionnaire, see appendix A

V.2 Discussion of Common and Diverging Views

Table I shows clearly, that only Sweden, U.K. and USA are currently performing studies directly related to DCH. In the US it is determined /26/, that DCH is a major driver of the uncertainties in risk for PWR plants being analyzed, particularly related to early containment failure. But no consensus currently exists on this special issue in the USA between various interested parties /26, 27, 28/. However, work is ongoing on the final version of NUREG-1150 which may alter the degree of consensus.

Because of other safety reasons, procedures are provided for accident management in France and FRG which also decrease the probability of DCH considerably. Special bleed and feed procedures together with the possible use of alternate low pressure injection systems to prevent core melt require a system depressurization, leading to a low pressure accident scenario, thus preventing DCH.

In other countries, the possibility for a rapid system depressurization to prevent DCH is still under consideration.

Differences in views exist also about the effect of details of cavity design and adjacent rooms in the lower part of the containment together with the influence of water in the cavity during blowdown of molten material together with gas. It can be stated, that the influence on DCH of special plant features (cavity design, RPV-failure mode) and different accident sequences is still being investigated.

VI. DISCUSSION OF KEY ISSUES

The key issues related to direct containment heating are discussed below under the following six categories.

1. Uncertainties in initial conditions
2. Uncertainties in ex-vessel processes and phenomena
3. Need for further analytical development
4. Concern with experimental approaches
5. Efficacy of accident management schemes
6. Impact on risk

VI.1 Uncertainties in Initial Conditions

There is widespread agreement among those who have addressed the DCH problem that a major source of uncertainty in whether a core meltdown accident scenario will lead to DCH is the initial physical conditions of the core melt just prior to failure of the primary system boundary. The reason for this uncertainty is that there is currently no reliable prediction of the details of the in-vessel core degradation and meltdown processes that would allow the initial conditions for the DCH ex-vessel scenario to be specified. Section II.1 provides the in-vessel physical processes and phenomena that are important to DCH. The three most significant issues here are:

- i) where the primary system will be initially breached and the time dependent behaviour of the size of the breach;
- ii) what is the pressure in the vessel at the time of breach and what is the subsequent depressurisation rate; and
- iii) what are the characteristics (mass, temperature, composition) of the core debris on the lower head of the vessel prior to failure.

It is expected that the in-vessel meltdown progression will be influenced by the specific design of the reactor internals. The potential for natural circulation of hot gases and the mode of

core debris relocation depend on reactor design (as well as the operational conditions that have led to the core melt condition).

VI.2 Uncertainties in the Ex-Vessel Processes and Phenomena

The ex-vessel processes and phenomena that are related to DCH are discussed in Section II.2. The early focus of analysis and experiments was on the question of the extent to which core debris would be transported from its initial discharged location in the reactor vessel to the upper regions of the containment. The earliest versions of the DCH scenario envisioned fine particles of core debris ejected into the containment atmosphere where they would thermally and chemically interact to produce a rapid, large pressure pulse on the containment. As the analysis and experiments proceeded, specific subissues related to the DCH scenario received closer attention and scrutiny.

Uncertainties abound in the area of ex-vessel phenomena and processes. The subareas of interest can be roughly divided into: initial conditions; effects of water; debris transport; local containment atmosphere conditions. A good discussion of uncertainties in the ex-vessel areas related to DCH is contained in reference /23/.

Particular focus has been placed on the role of steam during the initial phases of the high pressure melt ejection of core debris into the reactor cavity region. A current view is that metallic debris and steam would react extensively while the debris is still in the reactor cavity region. This would lead to production of large amounts of hydrogen. The hydrogen could then easily (relative to debris transport) migrate to the upper region of the containment. Once in the containment atmosphere, the possibility of burning of hydrogen has been posed, even in the presence of large quantities of steam because the atmosphere is very hot. Thus there would be a large contribution to the containment pressure load from a hydrogen burn.

VI.3 Need for Further Analytical Development

Reliable upper bounds to the containment pressurization from DCH can be calculated on the assumption of complete chemical reaction and adiabatic equilibration of specified amounts of core debris with the containment atmosphere. Such calculations show a potential for significant overpressurization of the containment in some cases. However, these calculations may greatly overestimate the pressurization because they do not account for the dynamic processes that control the rate, and ultimately the degree, of DCH. The current analytical research effort is aimed at producing more realistic predictions of containment pressurization, by including models of the important dynamic processes. This is desirable for two reasons:

- i) to produce a more realistic, but perhaps still bounding prediction of containment pressurization for the purpose of obtaining a measure of the safety significance DCH;
- ii) to produce a "best estimate" prediction of the threat from DCH in order to aid accident management decisions.

Although current "lumped-parameter" approaches to the modeling of debris dispersal and containment behavior (see section III.2) include some rate limiting processes, this approach may not be adequate to remove all of the major conservatisms in the predictions. In particular, Ginsberg and Tutu /29/ note that lumped-parameter methods do not account for potential large variations in hydrogen and steam concentration (and other parameters) within the reactor cavity and adjacent subcompartments of the containment. Thermal and chemical phenomena depend on local conditions and on the details of the flow patterns within these regions. Therefore there may be a need for more detailed (e.g. three-dimensional, finite difference) techniques to be used to improve on best estimate predictions of DCH. However, it is not clear that a detailed analysis,

using three-dimensional flow modeling, could itself be the basis for a reliable assessment of the risk from DCH.

VI.4 Concerns with Experimental Approaches

Experiments aimed at understanding the ex-vessel aspects of DCH phenomena are subject to three general concerns that tend to plague experiments more generally in the severe accident area. These are: limitations due to the use of simulant materials for core debris and related materials; limitations due to reduced scale in the experiments relative to the full reactor size; limitations due to the absence of configurational and structural details in the experiments relative to the actual reactor design. Currently there is inadequate assurance that the data obtained with simulants will be applicable to prototypic reactor conditions. The potential for experiments to provide an understanding of the mitigation and trapping of ejected debris by structures in and near the reactor cavity region is also affected by scaling. Of course, the absence of modeling of structure in some experiments will shed no light on the potential for trapping or mitigation of flowing debris. Limitations and problems with scaling are discussed in references /23/ and /28/.

The above considerations lead to the conclusion that theoretical understanding, of the phenomena occurring during DCH, is an essential link between experiments and plant predictions. Separate effects experiments, such as those involving low temperature simulants (see section III.1) are an important step in the development of phenomenological models. However, the strong coupling between thermal effects and fluid flow implies that direct extrapolation of such experiments is not appropriate. Finally, because of the complexity of the potential phenomena envisioned to be important to the DCH scenario and the range of reactor geometries and accident sequences which are potential candidates for the DCH scenarios it is expected /28/ that experimental programs that might help reduce uncertainty in risk for DCH will not do so for a number of years.

Furthermore, experiments which would support first principles analyses of DCH are difficult and measurement of the parameters needed to describe the microphysics that detailed modeling is based on will require extensive instrumentation development /30/.

VI.5 Efficacy of Accident Management Schemes

As is discussed in Section IV.1, and Section V, the main accident management scheme identified by the participating OECD countries is depressurization of the reactor system before high pressure melt ejection could occur. In this sense, depressurization is regarded as a preventive (for DCH) measure.

For boiling water reactors, a large capacity, fast acting depressurization system currently exists in the reactor design, (i.e., the automatic depressurization system - ADS) and thus the key issue for BWRs is the risk-relevance of high pressure scenarios (where ADS is postulated to fail) at the plant in question.

For pressurized water reactor, the central issues are whether the primary system can be depressurized sufficiently rapidly to avoid high pressure melt ejection and whether the "cutoff pressure" (below which high pressure melt ejection is not a threat) for high pressure melt ejection is sufficiently high to allow timely depressurization. Furthermore, it has been noted that depressurization of the primary system to avoid high pressure melt ejection has the (competing risk) effect of increasing the probability of in-vessel steam explosions because the latter are expected to be more likely under low pressure conditions.

As is noted in Section IV.2, ex-vessel mitigative measures for DCH have received less attention than depressurization of the primary system. The efficacy of any ex-vessel measure must naturally be measured against the limitations in the understanding of ex-vessel physical processes and phenomena.

The efficacy of having water in the reactor cavity prior to vessel failure is not well understood. The ANL experiments suggest that quenching of debris by water can mitigate the containment pressure rise. SNL analyses indicate that water co-dispersed with core debris may enhance the pressure rise depending upon the amount of water co-dispersed. Mitigative measures that would tend to inhibit debris dispersal to the containment dome area would have the effect of limiting direct debris particle participation in chemical and thermal interactions in the dome area. On the other hand, an increase of the residence time for debris in the cavity and lower containment regions could enhance the production of hydrogen that would result from the reaction of the metallic component of the debris with the steam.

Finally, the extent to which the introduction of inert gases to the containment atmosphere would prevent (or limit) hydrogen combustion in the containment dome area, will depend on the actual requirements for the combustion of hydrogen in the multicomponent, high-temperature atmosphere expected for DCH conditions.

VI.6 Impact on Risk

The ultimate question for a reactor safety activity related to DCH is: what is the relevance of DCH to the risk profile for the plant in question? A current answer to this question can be found in /26/. There it is shown that DCH controls the uncertainty in the conditional probability of early containment failure (given a core melt) and hence the prediction of early fatalities for the pressurized water reactors with large dry containments that were evaluated. Reference /26/ also provides the relative risk impact of DCH. This result was obtained by an expert opinion process that has been widely reviewed by the reactor safety community. As a result, this process and the specific approach to the evaluation of the DCH scenario is currently being revised for the forthcoming revision of /26/.

Because there is the possibility of depressurization of the primary system before high pressure melt ejection and because there are large uncertainties in many of the phenomena and processes that control the DCH scenario (particularly the initial physical conditions), the impact of DCH on risk has been assessed by some /27 and 31/ to be insignificant while in some countries there are programs aimed at elucidating the course of events for DCH and ultimately its impact on risk.

VII CONCLUSIONS AND RECOMMENDATIONS

Both experimental and analytical investigations have been performed on DCH, in some CSNI countries, for certain PWR plants with "open reactor cavities". The experimental investigations can be categorized as either high temperature melt experiments or hydrodynamic dispersal experiments. The former have been conducted at Sandia and Argonne National Laboratories and use thermite or corium to investigate debris behavior in scaled geometries. The hydrodynamic experiments are performed at Argonne, Brookhaven, and Winfrith and use room temperature fluids with transparent scaled cavity models to observe dispersal phenomena.

The analytical investigations include code development and applications in the USA and UK. Models are being developed for discharge and cavity phenomena and related thermodynamic loads in the containment.

The ex-vessel task group should maintain cognizance of developments in the understanding of the ex-vessel aspects of DCH resulting from the national research programs. There is a possibility that these research programs will show that DCH is not a threat for certain containment types or, at least, that the threat is significantly less than that which is currently estimated. However, many of the complexities leading to the current uncertainty in our understanding of DCH may not be resolved in the short term. Therefore the ex-vessel task group should focus its effort on accident management for

DCH with the highest priority given to approaches involving depressurisation of the primary system. An important aspect of this work should be the assessment of the relative risks for which it is important that estimates of the actual threat from DCH are as realistic as possible.

Depressurisation of the reactor cooling system is the only measure that has so far been identified as a possible means of preventing DCH. Whilst some countries have, or intend to introduce, procedures involving depressurisation of the primary system of a PWR, these measures are primarily aimed at reducing the probability of core melt and to mitigate the consequences of a possible gross head failure of the RPV in the case of core melt. As a result of these procedures, FRG and France in particular have a very different attitude to DCH from the US and UK.

Other countries are considering depressurisation of the system specifically to prevent DCH in the event of imminent core melt at high system pressure.

For mitigative measures the main conclusion is that for the three approaches that have been identified, the overall benefit is not clear because there are competing risks to be considered. However, the ex-vessel task group should maintain cognizance of possible future developments in these areas.

Future work of the task group should concentrate on philosophical and technical aspects of system depressurization as a preventive measure for DCH in different member countries. With respect to the discussions on aerosol distribution and source term within OECD/CSNI working groups, the influence of DCH should be taken into consideration.

VIII REFERENCES

- /1/ M. Pilch and W. Tarbell, "High Pressure Ejection of Melt from a Reactor Pressure Vessel - The Discharge Phase", NUREG/CR-4383 (1985).
- /2/ J.E. Brockmann and W.W. Tarbell, "Aerosol Source Term in High Pressure Melt Ejection", Nuc. Sci. and Eng. 88 (1984).
- /3/ W. Frid, "Behaviour of a Corium Jet in High Pressure Melt Ejection from a Reactor Pressure Vessel", Dissertation submitted to Department of Nuclear Reactor Engineering, Royal Institute of Technology, Stockholm, Sweden (1987), NUREG/CR-4508 (1988).
- /4/ W.W. Tarbell et al "Pressurized Melt Ejection into Scaled Reactor Cavities", NUREG/CR-4512 (1986).
- /5/ B.W. Spencer, D. Kilsdonk, J.J. Sienicki and G.R. Thomas, "Phenomenological Investigations of Cavity Interactions Following Postulated Vessel Melt Through", Proc. Int. Meeting on Thermal Reactor Safety, Chicago (1983) NUREG/CP-0027, Vol.2.
- /6/ R.V. Macbeth and R. Trenberth, "Experimental Modelling of Core Debris Dispersion from the Vault under a PWR Pressure Vessel, Part 1: Preliminary Experimental Results", AEEW-R 1888 (1987).
- /7/ P.W. Rose, "Experimental Modelling of Core Debris Dispersion from the Vault under a PWR Pressure Vessel, Part 2: Results Including the Instrument Cable Support Structure", AEEW-R 2143 (1987).

- /8/ M.Pilch, W.W, Tarbell and J.E. Brockmann, "The Influence of Reactor Geometry on the Behaviour of Dispersed Debris", SAND85-1725C (1985).
- /9/ D.C. Williams et al., "Containment Loads Due to Direct Containment Heating and Associated Hydrogen Behavior: Analysis and Calculations with the CONTAIN Code," NUREG/CR-4896, May 1987
- /10/ W. Tarbell, J. Brockmann and M. Pilch, "High Pressure Melt Ejection Streaming (HIPS) Program Plan", NUREG/CR-3025 (1984).
- /11/ B.W. Spencer, L.M. McUmbur and J.J. Sienicki, "Results and Analysis of Reactor Material Experiments on Ex-Vessel Corium Quench and Dispersal", Proc. Int. meeting on Thermal Nuclear Reactor Safety , Karlsruhe (1984).
- /12/ N.K. Tutu, T. Ginsberg et al., "Debris Dispersal from Reactor Cavities during High Pressure Melt Ejection Accident Scenarios", NUREG/CR- , to be issued Summer, 1988.
- /13/ K.Y. Huh, M. Corradini and G. Moses, "MI-HP Module for the Cavity Phenomena in a High Pressure Core Meltdown Accident Sequence", University of Wisconsin, UWRSR 31.
- /14/ B.W. Morris and R.V. Macbeth, "Experimental Modelling and Computer Simulation of Core Debris Dispersal", Proc. IAEA/NEA Int. Symposium on Severe Accidents in Nuclear Power Plants, Sorrento (1988).
- /15/ J.J. Sienicki, B.W. Spencer and D.Squarer in Heat-Transfer-Niagara Falls 1984 ed. N.M. Farukhi, AICLE Symposium Series, No. 236, Vol. 80.

- /16/ T. Ginsberg and N.K. Tutu, "DHCVIM - A Direct Heating Containment Vessel Interactions Module", AIChE Symposium Series, No. 257, Vol. 83, p. 347, 1987 (International Heat Transfer Conference - Pittsburgh 1987).
- /17/ M. Pilch and W.W. Tarbell, "Preliminary Calculations on Direct Heating of a Containment Atmosphere by Airborne Core Debris", NUREG/CR-4456 (1986).
- /18/ A.A. Amsden et al, "KIVA: A Computer Program for Two-and Three-Dimensional Fluid Flows with Chemical Reactions and Fuel Sprays", LA-10245-MS (1985).
- /19/ J.R. Travis, "HMS: A Computer Program for Transient, Three-Dimensional Mixing Gases", LA-10267-MS, NUREG/CR-4020 (1984).
- /20/ Kersting, E., Rohde, J.: Analysis of Selected Accident-Management Measures for a German PWR
IAEA International Symposium on Severe Accidents in Nuclear Power Plants; Sorrento/Italy, March 1988
- /21/ Gruner, P., Heuser, F.W., Rohde, J.: German Risk Study, Phase B. Results on Severe Accident Analysis
GRS-Presentation on P.S.A. Meeting,
Zürich/Switzerland 1987
- /22/ P.Bystedt, "The Swedish Programme for Mitigation of Core Melt Consequences", presented at CEC Seminar on STUDIES ON SEVERE ACCIDENTS IN LIGHT WATER REACTORS, Brussels, November 10-12, 1986
- /23/ "Uncertainty Papers on Severe Accident Source Terms".
NUREG-1265, Chapter 4, U.S. Nuclear Regulatory Commission, May 1987

- /24/ "Summary of DCH Research Review Group Meeting, June 18-19, 1987", U.S. Nuclear Regulatory Commission Memorandum (R. Meyer to M. Silberberg), September 29, 1987
- /25/ Presentation on "Approach to DCH in the Advanced Reactor Severe Accident Program of the U.S. Department of Energy", presented at Brookhaven National Laboratory, January 1988
- /26/ "Reactor Risk Reference Document" (Draft for Comment) NUREG-1150, U.S. Nuclear Regulatory Commission Appendix J.5, February 1987
- /27/ IDCOR Technical Report 85.2: Technical Support for Issue Resolution", Atomic Industrial Forum, Chap. 9, July 1985
- /28/ H.Kouts, "Review of Research on Uncertainties in Estimates of Source Terms from Severe Accidents in Nuclear Power Plants", NUREG/CR-4883, Section 4.1, April 1987
- /29/ T. Ginsberg und N.K. Tutu, "BNL Recommendations for DCH Analysis," Presented at USNRC DCH Research Review Group Meeting, Bethesda, MD, June 18, 1987.
- /30/ Letter: Ivan Catton to Dean Houston on Direct-Containment Heating Research Group Meeting 18-19, June, Bethesda, MD July 3, 1987
- /31/ Letter: A. L'Homme to V. Riebold, April 9, 1987, on point of view of French OECD/CSNI participants on subject of direct containment heating accidents
- /32/ N.K. Tutu, T. Ginsberg, et al, "Debris Dispersal from Reactor Cavities During High Pressure Melt Ejection Scenarios (to be published).

/33/ D.C. Williams and D. Louie, Transactions of the American Nuclear Society, 1988 ANS/ENS Meeting, October 1988, Washington, D.C.

APPENDIX A

DCH-Questions

1. Is DCH being addressed in any safety assessments being performed in your country?
2. Are these investigations related to PWRs and/or BWRs?
3. Are there any experimental investigations?
4. Are there any model development/analysis?
5. Are there any investigations related to boundary conditions for high-pressure melt ejection i.e. core degradation, primary system failure modes?
6. Are there any investigations of ex-vessel dynamics?
7. Are there any preventive and/or mitigative actions or design features being considered in relation to DCH?
8. What are the key cavity and containment design features related to DCH?

OECD

In 1948, the United States offered Marchall Plan aid to Europe, provided the war-torn European countries worked together for their own recovery. This they did in the Organisation for European Economic Co-operation (OEEC).

In 1960, Europe's fortunes had been restored; her standard of living was higher than ever before. On both sides of the Atlantic the interdependence of the industrialised countries of the Western World was now widely recognised. Canada and the United States joined the European countries of the OECD to create a new organisation, the Organisation for Economic Co-operation and Development. The Convention establishing the OECD was signed in Paris on 14th December 1960.

Pursuant to article 1 of the Convention, which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development 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 Signatories of the Convention were Austria, Belgium, Canada, Denmark, France, the Federal Republic of Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries acceded subsequently to the Convention (the dates are those on which the instruments of accessions were deposited); Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971) and New Zealand (29th May 1973).

The Socialist Federal Republic of Yugoslavia takes part in certain work of the OECD (agreement of 28th October 1961)

NEA

The OECD Nuclear Energy Agency (NEA) was established on 20th April 1972, replacing OECD's European Nuclear Energy Agency (ENEA, established on 20th December 1957) on the adhesion of Japan as a full member.

NEA now groups all 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 cooperation 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.

This is achieved by:

- encouraging harmonization of governments' regulatory policies and practices in the nuclear field, with particular reference to the safety of nuclear installations, protection of man against ionizing radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;
- keeping under review the technical and economic characteristics of nuclear power growth and of the nuclear fuel cycle, and assessing demand and supply for the different phases of the nuclear fuel cycle and the potential future contribution of nuclear power to overall energy demand;
- developing exchanges of scientific and technical information on nuclear energy, particularly through participation in common services;
- setting up international research and development programmes and undertakings jointly organised and operated by OECD countries.

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

CSNI

The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of scientists and engineers who have responsibilities for nuclear safety research and nuclear licensing. The Committee was set up in 1973 to develop and coordinate the Nuclear Energy Agency's work in nuclear safety matters, replacing the former Committee on Reactor Safety Technology (CREST) with its more limited scope.

The Committee's purpose is to foster international cooperation in nuclear safety amongst the OECD Member countries. This is done in a number of ways. Full use is made of the traditional methods of cooperation, such as information exchanges, establishment of working groups, and organisation of conferences. Some of these arrangements are of immediate benefit to Member countries, for example by improving the data base available to national regulatory authorities and to the scientific community at large. Other questions may be taken up by the Committee itself with the aim of achieving an international consensus wherever possible. The traditional approach to cooperation is reinforced by the creating of cooperative (international) research projects, such as PISC, LOFT and TMI-VIP, and by the organisation of international standard problem exercises for testing the performance of computer codes, test methods, etc. used in safety assessments. These exercises are now being conducted in most sectors of the nuclear safety programme.

The greater part of the CSNI cooperative programme is concerned with safety technology for water reactors. The principal areas covered are operating experience and human factors, coolant system behaviour, various aspects of structural materials testing, the confinement of accidental radioactive releases, accident management, 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.

The Subcommittee on Licensing, consisting of the CSNI Delegates who have responsibilities for the licensing of nuclear installations, examines a variety of nuclear regulatory problems and provides a forum for the review of regulatory questions, the aim being to develop consensus positions in specific areas.

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