HYDROGEN MANAGEMENT TECHNIQUES
IN CONTAINMENT

Report by a Group of Experts

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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS
OECD NUCLEAR ENERGY AGENCY
HYDROGEN MANAGEMENT TECHNIQUES
IN CONTAINMENT

Report by

CSNI's Task Group on Containment Aspects
of Severe Accident Management (CAM)

February 1993

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EXECUTIVE SUMMARY

While small volume containments with pressure suppression systems are inerted during normal power operation to prevent any hydrogen combustion, deliberate ignition systems are installed to cope with severe accident conditions in containments with ice condensers and of Mark III type. This is to limit the hydrogen concentration in the containment atmosphere by an early ignition of combustible gas mixtures.

Currently no requirements have been established worldwide on H₂ control during severe accidents in large dry containments of PWR's. The threats to the integrity of this type of containment, posed by hydrogen combustion are valued differently in published risk investigations.

Essential for the control of the risk associated with the hydrogen release into the containment is the knowledge of the composition of the atmosphere during the progress of the accident.

It should be pointed out that various hydrogen detection and control measures are at different stages of development. Individual judgement must be exercised in each specific application. Research work on hydrogen mitigation measures for large dry containments was mainly performed during the last two years in Germany. The use of systems, based on deliberate ignition and catalytic acting devices or a combination of both was investigated.

The actual status on the hydrogen detection and control in different OECD Member countries indicates that the systems existing for design basis accidents can well be regarded as sufficient, while the systems for hydrogen management under severe accident conditions need further completion and additions in most countries to cope adequately with a severe accident situation.
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1. INTRODUCTION

The reactor safety community has always been aware of the possibility that hydrogen may be generated during an accident in a LWR plant. Therefore, regulatory requirements have been fixed in different countries to cope with the long-term hydrogen generation and distribution inside the containment in a post LOCA situation.

In this context past considerations have tended to focus attention on accidents where the generation of hydrogen is limited by the operation of the emergency core cooling systems (ECCS), limiting the extent of the in-core metal-water reaction at low values. The radiolysis of water in the core and in the containment sump together with the possible corrosion of metals and paints in the containment are both relatively slow processes. The timescale involved in the generation of hydrogen in sufficient quantity as to approach the flammability limit allows the initiation of different measures to control the amount of hydrogen in the containment atmosphere and to prevent any burning. Provisions have been made in most plants to keep the local hydrogen concentration below 4 Vol.-% by means of mixing devices and recombiners.

The degraded core accident at Three Mile Island led to a general reexamination of the potential threat posed by hydrogen in the case of severe accidents. In the case of a severe accident, the exothermic metal-water reactions inside the reactor pressure vessel (in-vessel) and under special conditions also in the containment (ex-vessel) are of main concern, as they lead to high release rates of hydrogen to the containment atmosphere.

For long-term accident management, the sump water radiolysis becomes important, also for pre-inerted BWR containments, due to the oxygen generation.

During the evolution of a severe accident, local high hydrogen concentrations could be reached in short times, leading to a flammable gas mixture. In some situations local high steam concentrations could prevent for some time any burning due to inertisation.

This could result in local hydrogen accumulation, with the potential to reach detonation limits after steam condensation following spray ignition or by long time cooling down of the containment atmosphere.

In the following chapters various hydrogen management strategies, their effectiveness and qualification problems will be discussed. The main focus of this paper is on control of hydrogen in the containment. Design measures for prevention of hydrogen generation are not treated.

Due to different reactor systems and containment types in the OECD Member countries, no definite recommendations for special strategies to cope with the hydrogen in the case of a severe accident are given in this report.
2. THE OBJECTIVE OF VARIOUS HYDROGEN MANAGEMENT TECHNIQUES

The objective of plant internal emergency protection measures concerning hydrogen in the containment atmosphere, is directed towards the prevention of a failure of the containment structure leading to an uncontrollable release of radioactive materials into the environment. Hydrogen combustion may endanger the integrity and leaktightness of the containment during the progress of a severe accident as well as during the long-term post accident phase, unless design provisions protect essential equipment from burns under controlled conditions. Challenges to containment integrity may arise from:

- High pressure and temperature loads on the structures of the containment resulting from deflagrations as well as from faster reactions extending up to the type of detonation (quasi-static pressure loads, formation of pressure waves, local heating of the structure of the containment, etc.).

- Endangering of safety relevant technical equipment specially required to limit the consequences of accidents due to pressure, pressure differences, high local temperatures, also missiles as well as collapsing of partitioning walls, etc. Pump and valve drives, valves and flaps for containment isolation, electrical cable chains, as well as the instrumentation installations should be mentioned here.

- Impact loads on the structures of the containment by missiles after a local hydrogen detonation.

The present discussion on the measures against hydrogen (Fig. 1) can be divided into two fundamental strategies:

- prevention of the formation of burnable gas mixtures by inerting the atmosphere of the containment, and
- mitigation of the consequences of possible combustion by limiting the local hydrogen concentration.

Inerting of the containment atmosphere is possible before the occurrence of an event leading to high hydrogen generation or when symptoms and measured information during the progress of an accident would indicate that threshold values of the design basis could be exceeded.

In case of pre-inerting, the containment atmosphere is inerted before the beginning of power operation. This measure will be primarily carried out for small volume containments equipped with a pressure suppression system. Post-inerting, i.e. inertisation during the progress of an accident is at present under discussion for large dry containments.

For the limitation of the hydrogen concentration in the atmosphere of the containment, two different methods have been examined or were realized already. In one case, deliberate ignition and hydrogen combustion will be carried out after the gas mixture has attained the limit of flammability. The goal here is to possibly burn the hydrogen at lower concentration
and also to reduce the oxygen concentration of the atmosphere. For the other case, hydrogen will be recombined with the atmospheric oxygen by catalysts with large surfaces already before hydrogen concentration reaches the flammability limit.

Additional measures which may help to reduce the risk to the containment are, for example:

- quenching of the molten materials relocated from the RPV after its failure, into the reactor cavity, in order to limit the long-term hydrogen generation. Prevention or limitation of the oxidation of molten metals.

- mixing of the containment atmosphere to prevent a high local hydrogen concentration by recirculation systems or asymmetric spray (fanning of convection).

- reduction of the impact of hydrogen burns by means of spray systems (initial pressure, temperature increase).

- release of the containment atmosphere via the vent system to reduce the initial pressure and the pressure peak in case of a hydrogen combustion.

Numerous additional suggestions as well as various preventive measures (i.e. fire-extinguishing medium, thermal recombinations) have been examined additionally /6/. In most cases, the effectiveness was low or the individual measures were not compatible with the existing safety concept of the plant (i.e. additional large penetrations trough the containment).

The following chapters will deal with the advantages or disadvantages of the measures already realised and also with those measures presently at the stage of development or under test.
3. ACCIDENT MANAGEMENT ASPECTS, GUIDELINES, AND TECHNICAL CRITERIA

Essential for the control of the risk associated with the hydrogen release into the containment is the knowledge of the composition of the atmosphere during the progress of an accident to

- recognize where and when burnable mixtures will form and whether high local hydrogen concentration will develop under the inerting steam conditions during given accident sequences.

- investigate the optimum time for the initiation of countermeasures during the progress of the accident.

- determine and control the efficiency of the initiated countermeasures.

- switch off acting operational systems like fans, air-coolers etc. when they are expected to aggravate the hydrogen situation.

- decide during the progress of an accident on the safety implication of the start-up of spray systems or the use of a filtered vent system.

Specially, the use of suitable operational systems and the functioning of safety installations available within the scope of plant internal emergency protection, should be coordinated with the measures for hydrogen management, so that they do not aggravate the total situation concerning the integrity and functioning of the containment, including possible subatmospheric conditions, liable to impair containment integrity.

In order to be sure about the performance of countermeasures a broad basis of analytical and experimental work is required. At first, the potential of a possible countermeasure should be explored on a theoretical basis and eventually be transformed into a practice related concept after additional experimental investigations. Such a measure should not be developed for a few predetermined accident sequences but it should cover a wide range of possible accident events. The measure should always integrate in its strategy and functioning characteristic symptoms of the accident progression. Principally, those type of measures are plant specific, specially the criteria for an optimal application.

For specific licensing requirements, rules, guidelines and criteria to prevent or to remove combustible gas mixtures exist in most countries, mainly for DBA’s.

For accident possibly exceeding the boundary values of the design basis (beyond DBA), for which the probability of occurrence is estimated to be extremely small, guidance is given only in few countries and for special containment concepts.

Following the severe accident at TMI-2 (USA) small volume containments equipped with a pressure suppression system (only for BWR plants) have been inerted with nitrogen
during power operation. These are mainly GE manufactured Mark I and Mark II containments in the USA, and other countries which have imported these plants, as well as modified version of these BWR plants in Japan, Sweden, FRG (only type 69) etc.

Guidelines and technical criteria exist to inert and deinert the containment and to control the degree of inerting during normal power operation.

Regulatory requirements also do exist for the installation of igniters in containments with ice condensers, and for Mark III type.

These requirements have been implemented individually by the licensing authorities of some other countries, e.g. by Switzerland. Currently no regulatory requirements have been established worldwide on $H_2$-control in large dry containments of PWR's.
4. CAPABILITIES OF VARIOUS SYSTEMS AND MEASURES

The goal of various hydrogen countermeasures has already been described in chapter 2. Subdivision of measures to prevent the formation of combustible gas mixtures as well as those measures having impact to limit or mitigate the consequences of hydrogen combustion is also reflected in the concepts of technical solutions.

Inerting the atmosphere in the containment is achieved when the fraction of the air within the closed room system is exchanged or reduced by an inert gas, for example nitrogen (N₂) or carbon dioxide (CO₂). In this way the oxygen concentration in the containment should be limited to below the flammability limit of the gas mixture i.e. below 5 Vol.-%. For pre-inerting the exchange of gas is carried out before the beginning or during the start-up for normal plant operation. This safety measure had been required by the USNRC for all BWR plants with Mark I and Mark II types of containment shortly after the accident at TMI-2 /2, 5/.

Inerting the atmosphere in the containment during power operation has become a prescribed measure practically for all small volume containments with pressure suppression systems. Such inerting is a perfect protection against a possible hydrogen combustion during the accident propagation and the post-accident phase. For the long-term, i.e. weeks and months after the occurrence of the accident, this measure is no longer considered to be a perfect protection against any combustion. The radiolysis of water enhanced by the enrichment of fission products in the water pool of the pressure suppression system or in the sump region of the drywell leads to the generation of hydrogen and oxygen. Essential in this case is the long-term generation of oxygen. Then, the limits of flammability could be reached again.

Therefore, an additional measure for inerting has to be planned for the long-term accident management.

Post-inerting of large dry containments is a possible measure after the plant personnel have recognized that the accident would develop to an uncontrollable event sequence beyond the design basis. Early and rapid inerting before exceeding the low flammability limit of gas mixture, has to be decided and introduced in order to be efficient during the progress of the accident. It is important, that such a measure could not be realized independently from the type and propagation of the accident. A clear criterion to carry out such a measure needs detailed investigations.

Such a measure should primarily be verified with respect to its actual feasibility and effectiveness under the prevailing boundary conditions and its compatibility with the existing safety concept, for example whether more pipe penetrations through the containment wall would raise the question of additional leakages. In the case of a liquefied gas injection into the containment atmosphere, a protection of safety relevant equipment against thermal shock loads has to be realized. Furthermore, it must be kept in mind that this option leads to a high pressure level at the beginning of a severe accident (venting could be required) and maintains the containment pressure on a higher level for long time (higher leak rates).

An additional possibility to prevent a hydrogen burn is given by the catalytic-recombination of hydrogen with the oxygen available within the containment. This method
has been developed as a matter of priority in the Federal Republic of Germany (see /7, 8/), especially for application within a large dry containment under accident conditions. Also in Canada, at the Whiteshell Laboratories, and in the ex-USSR some research work is in progress on this matter. The passive reaction already starts below the flammability limit of a hydrogen-air mixture and takes place also under the conditions of a high steam concentration (up to 95 Vol.-%). These are the main advantages of this method. During a continuous release of hydrogen the catalytic reaction proceeds optimally. On the other hand for a high peak release rate a longer reduction time is needed. The concepts presently discussed are based on plates coated on both sides, granulates, etc. to be kept ready for application, e.g. within boxes in the containment so that, when required, a large surface area for the reaction could be provided. Experiments tend to demonstrate the effectiveness of this method even if catalytic poisons are present (like CO, S, H₂BO₂), in the presence of lubricants dissolved in steam and certain aerosols /13/.

Experiments within large volumes (10 up to 600 m³) were performed in the last two years in Germany /1,7,21,22/. Further research on the optimization of such a system, appears to be useful.

Active recombiners are systems which rely on external sources of energy. As they have been intended for long-term removal of hydrogen after a LOCA, they are not sufficient in their capacity to remove hydrogen under severe accident conditions.

In case a hydrogen combustion cannot be prevented, the goal of the measures is then to mitigate its possible impacts. Primarily, such measures should be directed towards the prevention of a local or a large volume detonation. A locally limited detonation does not necessarily lead to the failure of the containment, especially in areas where strong concrete structures exist.

Highly turbulent deflagration belongs also to the class of reactions leading to extreme loads on the structures of the containment. Such a deflagration or a subsequent DDT (deflagration to detonation transition) could occur when hydrogen concentration is high (>12 Vol.-%) and steam concentration is low (<10 Vol.-%). A countermeasure should not approach this limit. In order to achieve this goal, the concept of deliberate ignition has been developed. The strategy consists in the earliest possible ignition of combustible gas mixtures in order to prevent further enrichment of hydrogen in the atmosphere or to reduce the oxygen concentration. Differences should be made here between the glow- and spark-plugs (e.g. see /11/) having high external power requirements, in contrast to spark-igniters having integrated batteries and igniters based on catalytic reaction (glow igniters) /9,12,20/. Functional tests exist for various types of igniters (/9,14,15,18/). Little data are available up to now on experiences about the effectiveness of a concept based on igniters where a chain of compartments is to be secured.

The majority of tests with spark-igniters and plugs have been performed in a single room geometry. Relevant new results /10,18/ of ignition and flame propagation experiments in multicompartment geometries (Model Containment Battelle/Frankfurt, HDR) where gained in the last two years in Germany. Important indications for the optimum number and arrangement of igniters within a chain of compartments as well as on the capacity of combustion in an atmosphere containing steam were derived from this programme. Moreover,
the programme showed that the concept of ignition is useful as a hydrogen mitigation measure for most accident scenarios and containment concepts. Contradictory opinions (e.g. /19/), especially about the possible formation of highly turbulent deflagration or even about a DDT during a controlled ignition, also exist.

During multiple combustion in individual rooms, care should be taken about temperature loads on technical equipment, for example, cables, instrumentation and valve drives.

Apart from the inerting of pressure suppression system containment of types Mark I and II, the measure of controlled ignition in individual plants, especially with ice condensers and Mark III containments, has been installed. Presently, the application of the concept of deliberate ignition in large, dry containments of PWR plants is under discussion in some OECD Member countries.

Also, the application of the concept of catalytic devices can be used to maintain the hydrogen concentration at a lower level, so that an unexpected ignition during short-term high hydrogen release can start from a lower base value.

Therefore, a combination of deliberate ignition and catalytic recombination, the so-called DUAL-concept, was developed and tested in Germany /18/. Test results showed that such a combination is effective in reducing hydrogen concentration under inerted and non-inerted conditions.

The following advantages are associated with the use of this concept in large dry containments:

- diverse system, local "back up" for recombiners or igniters
- continuous H₂ removal to keep the concentration low, also under steam inerted conditions
- in the case of a limited release of H₂ (e.g., TMI accident) burn could be prevented
- in case of the sudden strong increase in H₂ release or steam condensation during accident progression, burning starts from a lower level of H₂ concentration
- long-term effectiveness (radiolysis of sump water).

For both, deliberate ignition and the DUAL-concept, the layout and demonstration of their efficacy require the use of appropriate thermohydraulic computer codes, besides experimental results. Theoretical investigations are necessary to determine the main convection flow paths of the gases in the containment, relevant for the optimal location of igniters and catalytic devices, in addition to a demonstration of how effective such systems work during different accident scenarios.

The tests in the Model Containment of Battelle/Frankfurt /18/ and in the HDR containment /23, 24/ showed deficiencies in the computer simulation of hydrogen distribution (stratification, mainly in the containment dome) and flame acceleration in room chains. Code
improvements are in progress in different countries. At the moment, big uncertainties of code results have to be taken into consideration for the layout of such systems.

The possibility to remove hydrogen from the containment via a vent system also exists. This method is strongly limited in capacity and presumes that the vent system is designed against loads from hydrogen combustion.
5. EFFECTIVENESS AND QUALIFICATION

Fundamental differentiation should be made between the qualification of individual components to set up a concept and the effectiveness of such a concept under various parameters, determined by the geometry of the containment and its internals for different accident sequences. This is specially valid for those concepts based on deliberate ignition and on catalytic recombination.

Qualification tests concerning, above all, the individual components have to be carried out. Such a qualification programme, e.g. for a deliberate ignition concept, should include:

- Ascertainment of the lower flammability limit under various types of compositions of the atmosphere during accident progression
- Response time for ignition (specially for the catalytic igniters)
- Multiple ignitions (high temperature at the position of the igniter)
- The influence of catalytic poisons (iodine, CO, H$_2$BO$_4$) and dissolved lubricants in the atmosphere (-> catalytic igniters)
- Pressure and temperature transients
- Vibrational behaviour
- Influence of flow velocity on gas ignition or catalytic reaction
- Submergence test
- Determination of the frequency of ignition, intensity of sparks (-> spark igniters)
- Influence of radiation
- Thermal ageing
- Proof of time for battery discharge for sparks igniters.

In addition to the function of the individual components, the proof of the effectiveness of a system on which the concept is based is of primary importance. This implies demonstration of how much hydrogen can be burnt early without inflicting larger damages to the plant by the concept of deliberate ignition or with the concept of catalytic devices, whether the level of hydrogen concentration can be kept below the flammability limit.

Such proofs are imperatively required, especially in relation to the real conditions in a containment (multicomartment geometry) and in relation to the existing atmospheric conditions given by various accident sequences, for example high local steam concentration in the atmosphere. Functionability of igniters, recombiners, catalytic devices O$_2$ and H$_2$
measuring instruments and wiring should be demonstrated under severe accident conditions. To secure the function of such mitigation systems, a programme has to be scheduled for repeated in-service or performance testing.
6. SUMMARY

Especially after the degraded core accident at TMI-2, the reactor safety community has been aware of the potential threat to containment integrity posed by hydrogen. Combustible gas mixtures could be formed in short times during the progress of a severe accident, but local high steam concentrations are able to prevent any burning for some time. This results in hydrogen accumulation, with the potential to reach detonation limits, in the case of steam condensation, e.g. by a delayed spray initiation or long-term cooling down of the containment atmosphere. The situation could lead to containment failure.

As a consequence, small volume containments, equipped with a pressure suppression system, are inerted during normal power operation. These are mainly BWR containments of the types Mark I and II, as well as modified versions, e.g. in Sweden and Germany. For long term accident management, attention has to be paid to the sump water radiolysis due to oxygen generation, decreasing the level of inerting.

Deliberate ignition systems are installed in most containments with ice condensers and of the Mark III type.

Currently no requirements have been established world-wide on \( \text{H}_2 \) control during severe accidents in large dry containments of PWR's. The threats to the integrity of this type of containment, posed by hydrogen combustion, are assessed differently in different risk investigations (see /16, 17/).

It should be recognized that various hydrogen control measures are at different stages of development. Individual judgement must be exercised in each specific application. Research work on hydrogen mitigation measures for large dry containments was mainly performed during the last two years in Germany. The use of systems, based on deliberate ignition and catalytic acting devices or a combination of both was investigated.

The actual status on the hydrogen control in different OECD Member countries, based on a questionnaire (see APPENDIX 1), can be seen from Table 1 and 2. These tables indicate that the systems existing for design basis accidents in Member countries can be regarded as sufficient, while the systems for severe accident management need further completion and additions in most countries to cope adequately with a severe accident situation.
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APPENDIX 1

Status in OECD/CSNI Member Countries on the Installation of Hydrogen Countermeasures

Questionnaire on

HYDROGEN MANAGEMENT TECHNIQUES IN CONTAINMENT

(notice: please differentiate between systems being already installed in NPP’s, in the licensing process or under discussion)

1. Country:

2. Type of containment: (large dry, subatmospheric, etc.)

Systems for DBA (Licensing requirements)

3. Systems, installed to prevent a hydrogen burn:

4. Systems for hydrogen monitoring:

Systems for severe accidents (beyond DBA)

5. Systems to prevent a hydrogen burn or to keep the concentration low:

6. System for hydrogen monitoring:

7. Systems to manage the hydrogen measure: (activation, control of function, etc.)

8. Qualification and quality assurance:

(please fill up a page for each typical class of containment design)
<table>
<thead>
<tr>
<th>Country</th>
<th>Type of Reactor Containment</th>
<th>Design Basic Accident (DBA)</th>
<th>Severe Accidents (beyond DBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>PWR, large dry containment</td>
<td>R</td>
<td>H₂-igniters and catalytic recombiners are under consideration</td>
</tr>
<tr>
<td>Canada</td>
<td>CANDU, large dry, negative pressure, single unit</td>
<td>M</td>
<td>No formal decision has been taken yet</td>
</tr>
<tr>
<td></td>
<td>CANDU, large dry, negative pressure, multi unit</td>
<td>D, M</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>BWR, Type 69</td>
<td>2 external catalytic recombiners by choice for drywell and/or wetwell</td>
<td>I, mixing by sprays</td>
</tr>
<tr>
<td></td>
<td>BWR, Type 72</td>
<td>2 external catalytic recombiners by choice for drywell and/or wetwell</td>
<td>Inerting is under consideration</td>
</tr>
<tr>
<td></td>
<td>PWR, large dry</td>
<td>2 recombiners, internal and thermal or external and catalytic, mixing by blowers or other devices</td>
<td>Use of deliberate ignition and/or catalytic devices under consideration</td>
</tr>
<tr>
<td>Finland</td>
<td>BWR, Mark II</td>
<td>I, redundant recombination system</td>
<td>I, both wetwell and drywell inereted</td>
</tr>
<tr>
<td></td>
<td>PWR, large ice condenser containment</td>
<td>M, capability to use the plant off-gas recombiner system (non-safety graded)</td>
<td>Deliberate-ignition by glow plugs</td>
</tr>
<tr>
<td>France</td>
<td>PWR, large dry containment</td>
<td>R</td>
<td>Implementation of H₂-procedure under consideration</td>
</tr>
</tbody>
</table>

R: Recombiners  
I: Inerting  
M: Mixing System  
D: Deliberate Ignition  
F: Recirculation Fans

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Table 1 Hydrogen Management
Table 1 (continued) Hydrogen Management

<table>
<thead>
<tr>
<th>Country</th>
<th>Type of Reactor Containment</th>
<th>Design Basis Accident (DBA)</th>
<th>Severe Accidents (Beyond DBA)</th>
</tr>
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<tr>
<td>Spain</td>
<td>BWR, Mark I</td>
<td>No hydrogen recombiner Flammability limit not in case of DBA</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>BWR, Mark III</td>
<td>R</td>
<td>D (glow plug type)</td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>R, M</td>
<td>No decision has been taken yet</td>
</tr>
<tr>
<td>Sweden</td>
<td>BWR, Mark III</td>
<td>R, I with ( N_2 )</td>
<td>I, with ( N_2 )</td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>R</td>
<td>No decision has been taken yet</td>
</tr>
<tr>
<td>Switzerland</td>
<td>BWR, Mark I</td>
<td>R</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>BWR, Mark III</td>
<td>R</td>
<td>Ignition system</td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>R</td>
<td>No decision has been taken yet</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>PWR, large dry containment</td>
<td>No decision as yet</td>
<td>No decision has been taken yet</td>
</tr>
</tbody>
</table>

R: Recombiners  
I: Inerting  
M: Mixing System  
D: Deliberate Ignition  
F: Recirculation Fans
<table>
<thead>
<tr>
<th>Country</th>
<th>Type of Reactor Containment</th>
<th>Design Basic Accident (DBA)</th>
<th>Severe Accidents (beyond DBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>BWR, Mark I, II</td>
<td>I, R or other control measures</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>BWR, Mark III</td>
<td>R</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>PWR, Ice condenser</td>
<td>R, F</td>
<td>D, F</td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>R</td>
<td>No additional requirements for existing plants</td>
</tr>
<tr>
<td>Netherlands</td>
<td>BWR, pre Mark I</td>
<td>R, I</td>
<td>Inerting</td>
</tr>
<tr>
<td></td>
<td>pressure suppression containment</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>BWR, Mark I</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BWR, Mark II</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>R</td>
<td></td>
</tr>
</tbody>
</table>

R: Recombiners  
I: Inerting  
D: Deliberate Ignition  
F: Recirculation Fans  
M: Mixing System
<table>
<thead>
<tr>
<th>Country</th>
<th>Typical Reaction Containment</th>
<th>Severe Accident (Beyond DBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>PWR, large dry containment</td>
<td>Wide range of instrumentation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Instrumentation for containment pressure, radiation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and stack release. Post-accident sampling of containment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>atmosphere and sump water</td>
</tr>
<tr>
<td>Canada</td>
<td>CANDU, large dry, negative</td>
<td>No Information</td>
</tr>
<tr>
<td></td>
<td>pressure, single unit</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CANDU, large dry negative</td>
<td></td>
</tr>
<tr>
<td></td>
<td>pressure, multi unit</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>BWR, Type 69</td>
<td>Wide range of instrumentation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wide range of instrumentation</td>
</tr>
<tr>
<td></td>
<td>BWR, Type 72</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>Wide range of instrumentation</td>
</tr>
<tr>
<td>Finland</td>
<td>BWR, Mark II</td>
<td>Wide range of instrumentation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PWR, large ice condenser</td>
<td>Wide range of instrumentation</td>
</tr>
<tr>
<td></td>
<td>containment</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>PWR, large dry containment</td>
<td>Monitoring by grab samples</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>All plants have installed, a wide range of instrumentation,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>monitoring containment atmosphere conditions for pressure,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>temperature and radiation</td>
</tr>
<tr>
<td>Netherlands</td>
<td>BWR, pre Mark I, pressure</td>
<td>Monitoring provided</td>
</tr>
<tr>
<td></td>
<td>suppression</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>Monitoring provided</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sampling system has been added</td>
</tr>
</tbody>
</table>
### Table 2 (continued) Instrumentation for Detection and Control

<table>
<thead>
<tr>
<th>Country</th>
<th>Type of Reactor</th>
<th>Standard Basis Accident (DBA)</th>
<th>Severe Accidents (beyond DBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spain</td>
<td>BWR, Mark I</td>
<td>Oxygen analyzer, intake from various points</td>
<td>Same as in DBA</td>
</tr>
<tr>
<td></td>
<td>BWR, Mark III</td>
<td>H2-analyzer, intake from several points</td>
<td>Same as in DBA</td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>Westinghouse monitoring from 8 points, KWU monitoring from 11 points</td>
<td>Same as in DBA</td>
</tr>
<tr>
<td>Sweden</td>
<td>BWR, Mark III</td>
<td>Monitoring by gas chromatography</td>
<td>Post accident sampling system</td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>PWR-sensors based on catalytic principles (KWU-Typ WS85). Sampling system could be used</td>
<td>Post accident sampling system, extended range of catalytic sensors, up to 10 Vol-% H₂</td>
</tr>
<tr>
<td>Switzerland</td>
<td>BWR, Mark I</td>
<td>Monitoring system provided</td>
<td>DBA monitoring system</td>
</tr>
<tr>
<td></td>
<td>BWR, Mark III</td>
<td>Monitoring system provided</td>
<td>DBA monitoring system</td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>Monitoring system provided</td>
<td>no decision at the moment</td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>Monitoring system will be provided</td>
<td>Sampling of containment atmosphere to monitor radioactivity, humidity and hydrogen. Leak detection by sampling and monitoring</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>BWR, Mark I</td>
<td>Monitoring by grab sample</td>
<td>All plants have installed or plan to install wide range of instrumentation, monitoring containment atmosphere conditions for pressure, temperature and radiation</td>
</tr>
<tr>
<td></td>
<td>BWR, Mark III</td>
<td>Monitoring on-line or grab sample</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PWR, ice condenser</td>
<td>Monitoring on-line or grab sample</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>Monitoring provided</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>BWR, Mark I</td>
<td>wide range of monitors</td>
<td>Monitoring for containment pressure and radiation levels</td>
</tr>
<tr>
<td></td>
<td>BWR, Mark III</td>
<td>wide range of monitors</td>
<td>Additionally post accident sampling system has been installed</td>
</tr>
<tr>
<td></td>
<td>PWR, large dry containment</td>
<td>wide range of monitors</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 1: Different strategies and measures to cope with the $H_2$-problem during severe accidents
Appendix 2

List of Members of the CSNI-PWG4 Task Group on Containment Aspects of Severe Accident Management (CAM) (March 1992)

<table>
<thead>
<tr>
<th>Country</th>
<th>Name</th>
<th>Organization/Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>Mr. Benoît De Boeck</td>
<td>AVN</td>
</tr>
<tr>
<td></td>
<td>Mr. Albert Delbrassine</td>
<td>CEN/SCK Mol</td>
</tr>
<tr>
<td></td>
<td>Dr. Jean Snoeck</td>
<td>Tractebel</td>
</tr>
<tr>
<td>Canada</td>
<td>Dr. Gianni M. Frescura</td>
<td>Ontario Hydro</td>
</tr>
<tr>
<td>Finland</td>
<td>Mr. Timo J. Okkonen</td>
<td>STUK</td>
</tr>
<tr>
<td>France</td>
<td>Mr. Jacques Duco</td>
<td>CEA/IPSN (Chairman)</td>
</tr>
<tr>
<td>Germany</td>
<td>Mr. Jürgen Rohde</td>
<td>GRS*</td>
</tr>
<tr>
<td>Italy</td>
<td>Mr. Arnaldo Turricchia</td>
<td>ENEL</td>
</tr>
<tr>
<td>Japan</td>
<td>Dr. Kunihisya Soda</td>
<td>JAERI</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>Mr. Simon Spoestra</td>
<td>ECN</td>
</tr>
<tr>
<td>Spain</td>
<td>Mr. Fernando Robledo</td>
<td>CSN</td>
</tr>
<tr>
<td>Sweden</td>
<td>Dr. Gustaf Löwenhielm</td>
<td>Vattenfall</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Dr. Martin Baggenstos</td>
<td>HSK</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>Mr. Rodney L.D. Young</td>
<td>SRD</td>
</tr>
<tr>
<td>United States</td>
<td>Dr. Tim M. Lee</td>
<td>NRC</td>
</tr>
<tr>
<td></td>
<td>Mr. Walter F. Pasedag</td>
<td>DOE</td>
</tr>
<tr>
<td>Commission of the</td>
<td>Mr. Heinz Lenders</td>
<td>DG XII</td>
</tr>
<tr>
<td>European Communities</td>
<td>Mr. Henk van Rij</td>
<td>JRC Ispra</td>
</tr>
</tbody>
</table>

OECD Nuclear Energy Agency:

Dr. Jacques Royen (Secretary)

* Mr. Rohde prepared the successive versions of the draft of this report.
OECD

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 were 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.

NEA

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 in Vienna, with which it has concluded a Co-operation 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. It was set up in 1973 to develop and coordinate the activities of the Nuclear Energy Agency concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations. The Committee's purpose is to foster international co-operation in nuclear safety amongst the OECD Member countries.

CSNI is sponsoring several Senior Groups of Experts and Principal Working Groups (PWG's). PWG4 is dealing with the confinement of accidental radioactive releases.