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POSITIVE/NEGATIVE ASPECTS OF MEASURES DESIGNED TO PROTECT THE CONTAINMENT

Report by a Group of Experts

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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS
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TASK GROUP ON CONTAINMENT ASPECTS OF SEVERE ACCIDENT MANAGEMENT
(CAM)

Positive/Negative Aspects of Measures Designed to Protect the Containment

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EXECUTIVE SUMMARY

Background and Purpose

The accident at Three Mile Island Unit 2 sparked considerable interest in the phenomenology of potential severe accidents in nuclear power plant. As the various international research programmes matured, it became increasingly apparent that plant operators might be able to lessen the severity of such accidents and mitigate their consequences by implementing an appropriate accident management strategy to protect the plant's containment. However, these strategies have both advantages and possible drawbacks. This report draws on the experience of Member States to present an overview of the present status of positive and negative aspects of measures designed to protect the containment.

Scope

Section 1 of this report introduces the report and explains its scope. In particular, it identifies those measures to protect the containment which will be considered in greater detail in later sections. Section 2 is a brief introduction to containment protection philosophy which addresses the role of containment and describes the range of possible hazards to the containment and how they might be reduced. Several important safety issues fall outside the remit of this status report and the section concludes by explaining some of them.

Section 3 describes in some detail the principal features of the various protection measures and techniques and how they might be used to protect the containment of Light Water Reactors; where necessary, their implementation on Pressurised Water Reactors is distinguished from that on Boiling Water Reactor. Because this report aims to give an overview rather than an assessment of the state-of-the-art, individual plants are not referred to except by way of illustration. Both this section and the next describe the positive and negative aspects of measures designed to protect the containment. The discussion in section 4 is presented in summary terms ("advantages" and "drawbacks") which highlight the significant aspects of each measure.

Conclusions

The following conclusions are reached concerning individual measures.

- Filtered containment venting systems can be designed and operated so that containment over-pressurisation is avoided. The main question to be decided is at what stage in an accident should venting be initiated.

- The use of spent fuel ponds as scrubbing pools is still under investigation so no firm conclusion can reached on its potential value.

- The use of spray systems could be an important part of containment management strategies for severe accidents, with special attention to possible hydrogen combustion.

- The effect of injecting water to flood a reactor cavity, whether wholly or partially, is still being investigated as a means of protecting the lower drywell liner in BWRs or the reactor vessel in low power-density PWRs.

- Various hydrogen management techniques involving igniters and recombiners are available. The particular characteristics of each type tends to complement those of other types and, given the benefit to be obtained by reducing the concentration of hydrogen in the containment, it could be prudent to install a variety of types.

- There appears to be little advantage gained by inerting containments once a severe accident sequence has started. Pre-inerting could be beneficial for hydrogen control provided the denial of free access to the containment is acceptable.

- Fan coolers can provide an alternative means of depressurising a containment provided certain questions concerning their operability can be answered satisfactorily. Other heat removal systems are very plant-specific; for example, external containment sprays are only effective if the containment wall has a sufficiently large area of high thermal conductivity.

The overall conclusion is that each of the proposed measures to protect the containment has both advantages and potential drawbacks, and that several systems are not yet fully developed. An evaluation is therefore needed to determine the benefit which may be gained from adopting a particular strategy. An important part of this evaluation must be an assessment of the effects of interactions between different systems, and conflicts of priority of operation where there is little interaction.

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1. Introduction

1.1 Purpose of the report

Most Light Water Reactors (LWRs) have containment systems to mitigate the effects of accidents involving a breach in the primary pressure circuit. In an accident, the containment must remain intact to perform its desired function.

Various events during the accident may threaten the integrity of the containment. To combat this, accident management provisions may be made. However, it is necessary to consider both positive and negative effects of these provisions since they could, at least in principle, increase the overall risk instead of reducing it. It is the purpose of this report to review this issue.

1.2 Scope of the Report

The CSNI Principal Working Group No. 4 on the Confinement of Accidental Radioactive Releases has recommended that the following containment protection measures be considered:

- filtered containment venting systems
- use of spent fuel ponds as scrubbing systems
- spray systems
- injection of water / cavity flooding
- hydrogen management
- pre / post inerting
- fan coolers and other heat removal systems

This report reviews the use of each of these, considers the potential positive and negative aspects, and draws overall conclusions on the existing consensus. It concentrates on the issues relevant to the question of containment accident management and reviews the extent to which these may be considered to be resolved.

1.3 Limitations of the Report

The Report is limited to the scope outlined above and also by being based on the information provided by the contributors from participating countries. It does not attempt to draw conclusions specific to one country or site but concentrates on general issues. Further, it does not address detailed cost/benefit analysis since this is very site-specific. Neither the level of detail nor the degree of site-specificity implied by this would be appropriate in a report of this nature. One consequence of this is that issues such as the interaction between phenomenological and operational factors which influence the development of possible accident management strategies for each sequence or threat are not discussed in any detail as they are too design-dependent.

1.4 List of Contributors to the Report

A list of contributors to this Report is given in Appendix 1. We are grateful to them for providing the information which made this report possible.

2. Containment Protection Philosophy

2.1 The role of containment

In LWRs the safe containment of radioactive fission products is achieved by enclosing them in a series of "Chinese boxes" (the principle of defence in depth). Thus they are held in the matrix of the oxide fuel pellet which is enveloped by the cladding of the fuel rod; this is then enclosed within the primary circuit which in turn is surrounded by the reactor building. This building, commonly called "the containment", is the final barrier between the core and the public. To ensure there is no substantial risk to public health and safety and to reassure a public concerned on such issues, it must be able to withstand the loads imposed on it by design basis accidents, and it is desirable that degraded core accidents also be contained.

This is achieved by detailed consideration of the types of accident that could occur to the plant and how these accidents might be expected to progress. The type, timing, size and duration of the loads imposed by the accident on the plant and containment must be taken into account and appropriate countermeasures developed. These loads may be mechanical (such as the impact of a missile generated by a bursting pressurised circuit), thermal (such as the attack of a molten core on the concrete basemat) or thermal-hydraulic (such as those due to hydrogen burns or the gradual pressurisation of the containment structure due to the decay heating from airborne fission products) and their differing natures call for different responses. It is the role of the containment to be able to provide all the responses necessary to minimise the risk of releasing fission products to the environment.

2.2 Description of hazards to containment

During a design basis accident the reactor core remains intact with a coolable geometry. The principal hazard is thus the pressurisation caused by the discharge of a somewhat radioactive mixture of water and steam to the containment.

If the accident progresses beyond the design basis, there are several possible additional threats to containment integrity, depending on whether or not the core is retained in the primary circuit. Thus at Three Mile Island for example, while the core remained in the pressure vessel the hydrogen generated by the zircaloy-steam reaction was released to the containment and caused some superficial damage when it ignited.

Current severe accident assessments have identified a number of ways in which there could be a significant threat to the containment. These all have their origins in the large amount of decay heat stored in the reactor's core and include:

- a steam explosion, either in-vessel or ex-vessel, sufficiently large to rupture the containment

- a molten core-concrete interaction which penetrates the basemat of the containment building

- long-term over-pressurisation of the containment building due to the build-up of non-condensable gases from a core- concrete interaction or from the decay heat generated by airborne fission products

- failure of the containment by the overpressures resulting from a hydrogen burn, the hydrogen being generated initially by reactions between steam and core and vessel materials (primarily the oxidation of the zircaloy cladding) and afterwards by radiolysis and by electrolytic reactions between steam or water and structural materials

- failure of the containment by overpressure due to the high pressure melt ejection / direct containment heating phenomenon

All save the last of these threats have been recognised for some considerable time and this Report is concerned with the various measures that have been or are being taken to minimise their severity.

2.3 How can the effects of these hazards be reduced?

The most effective way of protecting the containment during a severe accident is to stop the core degrading while it is still in the vessel, preferably as soon as possible. If this is not possible, there are two principal means of reducing the effects of these hazards. The first is to design the containment structure so that it is capable of withstanding any load imposed on it. There is a certain merit in designing a strong containment such as the large dry containment used for some PWRs since this allows for much greater flexibility in accident management with a greater reserve of safety. However, not all LWRs (BWRs in particular) are so equipped, nor on cost grounds is it feasible to construct an ultra-strong containment; moreover, the uncertainty attached to estimates of the possible loads makes it difficult to know precisely what to aim for.

The second means of reducing these hazards is to design and install equipment which will limit their severity. Thus damaging hydrogen burns could be avoided by removing oxygen from the containment atmosphere or by continually burning hydrogen as it was generated to prevent the build-up of a dangerous mass and concentration of a flammable mixture.

The measures listed in paragraph 1.2 have been selected as possible means of reducing hazards in this second way. The list is repeated with the intended aim of each measure below.

- filtered containment venting systems, to relieve containment overpressure

- use of spent fuel ponds as scrubbing systems, to remove aerosols from the atmosphere and to reduce containment pressure. In principle, this is a form of filtered containment venting, but it is treated separately here because it employs a different design concept

- spray systems, to cool the containment atmosphere by condensing steam and to remove aerosols in the atmosphere

- injection of water / cavity flooding, to cool the core should it melt through the bottom of the pressure vessel

- hydrogen management, to prevent the build-up of dangerous concentrations of flammable hydrogen

- pre / post inerting, a form of hydrogen management with special implications

- fan coolers and other heat removal systems, to reduce containment pressure

2.4 Safety issues not fully addressed by the measures considered here

Some of the main threats to the containment were identified in section 2.2 and a list of possible countermeasures was given in section 2.3. However, neither list was exhaustive and there are several important safety issues which are not addressed in this report.

The first of these is high pressure melt ejection followed by direct containment heating. Here, the core is assumed to melt down while the primary circuit is at high pressure. If the core is allowed to melt through the pressure vessel, the system pressure could expel it in whole or in part as fine particulate material. The resultant high heat transfer to and chemical reactions with the containment atmosphere could cause catastrophic overpressurisation of the containment building leading to early failure.

Another issue is that of resuspension of aerosols where steps taken to relieve the containment pressure set up flow patterns which cause deposited aerosols to re-enter the containment atmosphere from horizontal surfaces and pools of water, thereby necessitating a repetition of the measures taken to remove them in the first instance. If, however, the containment boundary had meanwhile been breached by whatever means, there could be a threat to public health caused by the delayed release of fission products.

A third concern would be the interaction between severe accident management procedures considered for the primary circuit and those proposed for the containment. For example, if core meltdown is perceived to be likely, depressurisation of the primary circuit to prevent a possible high pressure melt ejection scenario may create conditions which favour a damaging in-vessel steam explosion. Another example is the effect of containment venting on the net positive suction head of the Emergency Core Cooling pumps whose efficiency may thus be impaired. The choice of action to be taken may then depend on the assessed probability of occurrence and likely consequences of the possible events.

3. Description of Protection Measures and Techniques

3.1 Introduction

In this section a brief account will be given of each of the main methods used to manage conditions within the containment during a severe accident. These methods are usually designed to counter a specific threat which will be identified and both their positive and negative aspects will be described, as will the current status of their implementation in member countries.

3.2 Filtered containment venting systems

Objective

Unless successful accident management is implemented at an early stage in a severe accident, there is a risk that the containment may fail by overpressurisation. This could be caused in a variety of ways of which the long-term heating of the containment atmosphere by airborne fission products and the release of steam and non-condensable gases through a core-concrete interaction are two examples. The possibility of venting the containment while retaining the bulk of the fission products has been explored as a means both of preventing catastrophic overpressurisation of the containment and thus limiting the level of releases into the environment and of providing the operator with the best means for controlling the situation and maintaining containment function. In general, venting is not activated automatically. The pressure at which it is initiated should be well above the containment's design pressure but reasonably below its potential failure pressure to avoid as much as possible unnecessary activation of the filtered venting system.

The question of filtered containment venting systems was the subject of a CSNI Specialist Meeting [1]. The major contributions were made by the Federal Republic of Germany, France and Sweden and, in addition to describing systems which had been installed or which were planned for installation, addressed safety policy, design requirements, R&D issues and venting strategies. Contributions were also made by Finland, Italy, Switzerland and the United States. A Senior Group of Experts on Severe Accidents of the CSNI reviewed this meeting [2] andconcluded that, although the technical solutions proposed by the various countries (notably the Federal Republic of Germany, France and Sweden) differed significantly, these solutions all met the same requirements:

- the design rules throughout the installation must continue to be observed
- implementation of these systems must not worsen the accident, thus if fission products have been released to the containment then venting is a last resort
- conservative system design, with specific safety problems being identified and solved

- technical options selected on the basis of existing knowledge (except possibly for R&D needed on filters)
- modest cost of implementing the solutions

Different venting systems have been installed in or proposed for Boiling Water Reactors (BWRs) and Pressurised Water Reactors (PWRs) and these are considered separately below.

Application - BWRs

For BWRs both unfiltered and filtered venting systems exist which can both be used to prevent core melt or to mitigate its consequences.

Unfiltered Venting in BWRs

The accident scenario addressed by unfiltered venting in BWRs is one where a Loss of Coolant Accident (LOCA) occurs at a time when the pressure suppression system is unable to operate as designed. This could be due to significant leakage of water from the wetwell or to there being an open connection between the wetwell with the drywell, whether intended or not. The Emergency Core Cooling System (ECCS) is assumed to function correctly and so the release of fission products is limited to the activity of the primary circuit water and steam. Unfiltered venting may also be used to mitigate the consequences of an Anticipated Transient Without Scram which would otherwise overload the heat removal system. The system vents automatically - a rupture disc is installed - and the release of radioactivity to the atmosphere is considered to be sufficiently low that no filtration is needed. In the highly unlikely case that the accident progresses to a stage where core melt starts with a consequent major release of fission products, closure valves in the relief line would be secured to prevent such a release. In some reactors this closure is achieved automatically, whereas in others operator action is required.

Filtered Venting in BWRs

The aim of filtered venting in BWRs is to prevent late overpressurisation of the containment and to limit (or in some cases prevent) the release of radioactive materials to the environment to acceptable levels following a core melt sequence. The late overpressurisation of the containment may be due to a variety of causes: for example, the decay heat of the radioactive core whether directly through heat transfer from noble gases in the containment which pressurises the atmosphere directly, or indirectly by the evolution of steam through the contact of water with corium; or the generation of steam and non- condensable gases from a corium-concrete interaction.

Filtered venting systems can be designed to operate both automatically and manually, and system requirements generally demand that the control valves can be opened and closed repeatedly to reduce the containment pressure in a controlled manner. A common requirement is that the system is activated - generally by a rupture disk - once the containment pressure exceeds the design pressure. In some cases the system is activated by opening the valves, the rupture disk being used as a means of last resort if no steps to control the accident have been taken. The set point of the rupture disk is then between the design and failure pressures of the containment.

The filtration system that is used varies considerably. It has to be capable of absorbing a considerable amount of mass and energy and provide adequate decontamination before the water-steam-gas-particulate mixture is released to the environment. Among the techniques used are wet venturi scrubbers, dry filter beds and systems using nozzles, baffles and mixing elements; and combinations of these may be used in the same installation. Decontamination factors of up to 500-10000 for particulate material and greater than 1000 for elemental iodine are achievable [1].

Application - PWRs

Filtered vents have also been installed in or proposed for PWRs. PWRs for which filtered vents have been considered tend to have containments with greater free volume than BWRs and so there is less need to seek pressure relief through venting early in the accident sequence. However, this means that when it is required the containment atmosphere is likely to contain significant quantities of fission products and so filtration becomes essential. The design criteria are similar to those already noted for BWRs, except that decontamination factors for the filters are typically rather higher, by a factor of 3 for particulates and 10 for elemental iodine [1]. Despite this, countries possessing both BWRs and PWRs tend to specify a common decontamination factor for filters regardless of reactor type.

3.3 Use of spent fuel ponds as scrubbing pools

Objective

Spent fuel ponds contain large volumes of water and are designed both to keep fuel cool and to retain fission products. The need to provide adequate filtration for vented containments has prompted the idea of an alternative venting system using these ponds as aerosol and soluble vapour scrubbing pools and relieving the overpressure by discharging it through the filtered stack. This may be an attractive method where reactors have their spent fuel water pools located outside the reactor building.

Implementation

It is proposed to use a pipe to connect the containment atmosphere to the spent fuel pool, at some point below the water level. Should a severe accident occur, or if the pressure in the containment atmosphere were to rise above the design pressure, this line would be opened by manual intervention. The large water inventory in the pools would condense the steam and would retain most of the fission products provided the temperature within the pool remained low. At elevated pool temperatures the retention capability for fission products is reduced. Sufficient instrumentation should be available within the pool to terminate this type of accident management procedure at the appropriate moment.

If off-site or on-site power sources were available, the pool hall would be ventilated and the remaining fission products would be filtered and discharged at the stack. If all electrical power sources were lost, the ambient conditions in the fuel pool building could pose some problems, especially the hydrogen concentration and further study is required.

However, the need to take the station blackout case into account would depend on the outcome of a PSA study. For plants which are well protected against a station blackout it is not clear if sequences with a total loss of electric power are an important contributor to the overall risk.

3.4 Spray systems

Objective

The purpose of the containment spray system is, should an accident occur, to control the pressure within a containment by cooling and condensing steam from the atmosphere, and to remove airborne aerosols. The ability to use sprays is a common requirement for design-basis accidents; a question to be considered in developing severe accident management strategies is whether the cooling systems for the spray water can be maintained, or re-established within a reasonable time after a potential failure.

Implementation

Formal procedures for the use of sprays in severe accident management have been implemented in a few countries. The following, taken from reference [3], is an example of what might be required.

"As soon as possible after the start of the accident, water shall be supplied to the containment via the containment spray system. In order to achieve this with very high reliability, back-up sources of water to the spray system will be introduced. This will mainly consist of connections to diesel-driven pumps in the fire water system, but options for connecting mobile pumps may also be provided. By spraying water into the containment, pressure build-up by steam generation will be avoided and the pressure be kept below the design pressure of the containment for many hours. Furthermore, time is gained for actions to restore circulating cooling of the containment (loss of these systems is assumed). Also, radioactive aerosols are removed from the containment atmosphere and dissolved in the water. By successively filling water into the containment up to core level, all core material will be covered by water and cooled.

"In the BWR, due to the relatively small containment volume, it is foreseen that at some point during the filling-up of the containment relief of the compressed atmosphere in order not to exceed the design pressure will be required. For this purpose a venting system will be installed which will allow manual venting as well as automatic pressure relief. The vent line will contain a water scrubber, which will retain the fission products (excluding noble gases) so that in a typical case the release limit is met with a wide margin. The scrubber is designed for retention factors at least in the range of 100-500 depending on reactor type.

"In the PWR there is no need to vent the containment for a long time if containment spray water can be supplied within 5-6 hours after the start of the accident. Without water injection to the containment, the design pressure would be reached after this time and venting would be required. This is due to the fact that in the Ringhals type PWR containment, flow paths exist between the containment and the reactor cavity, so that there will be a considerable amount of water in the cavity. Steam will be generated by the residual power and a pressure build-up occurs in the containment, assuming loss of normal containment cooling. Also in the PWRs a containment vent of the same type as for the BWR will be installed in accordance with the strategy. This will facilitate venting of the containment without exceeding the release limits also in cases where containment spray water is not restored before the design pressure is reached.

"The outlined strategy puts a great emphasis on active operator intervention during an accident. In addition to the hardware installations, a great effort is therefore made to develop the software side e.g. developing procedures and training personnel to be able to properly evaluate and handle an accident situation."

3.5 Injection of water/cavity flooding

Objective

The injection of water into (and possible flooding of) the reactor cavity is mainly aimed at keeping in a coolable configuration the molten core debris (corium) which breached the reactor vessel bottom head. This is to prevent or minimise the thermal-chemical interaction between the corium and the cavity floor concrete. The production of non-condensable gases would thereby be reduced significantly, hence reducing the possibility of containment pressurisation, as would the erosion of the basemat resulting in a reduced likelihood of breaching the leak-tightness and integrity of the containment. Furthermore, the associated generation of aerosols, with their impact on the source term, could be strongly reduced. However, it should be noted that the limited amount of experimental data which is currently available suggests that flooding may not be effective if the corium thickness is too great and that the large quantities of steam which could be produced by debris-water interactions will need to be accounted for in assessing containment overpressure strategy.

Application - BWRs

For BWRs the penetrations in the lower drywell are vulnerable to damage from molten corium and so to protect them the compartment has to be flooded with water before pressure vessel melt-through. Since the floor area of the lower drywell is relatively large (typically varying between 45-135 m2), it is likely that the core will reach a coolable state after the pressure vessel melt-through. The core-concrete interaction may also be prevented.

The flooding can be accomplished with existing systems using the condensation pool water. It may be activated either automatically or manually and from more than one location within the plant. To achieve this, however, requires knowledge of the actual state of the core and the containment, thus additional instrumentation and new operating procedures are needed.

An example of how these issues have been addressed is as follows. Pressure-, temperature- and radiation-resistant instrumentation has been installed to monitor the containment condition. The new measurements include:

- drywell and condensation pool temperatures
- drywell pressure
- drywell and wetwell water level
- differential pressure between drywell and wetwell
- radioactivity in the drywell

New symptom-based operating procedures for severe accident management have also been developed for the plants.

However, there is a possibility that in exceptional conditions vessel melt-through may be followed by a steam explosion when the corium interacts with the water in the volume below the reactor vessel. The effect on the containment of a steam explosion will depend on its location and the strength of the surrounding structures.

Long term water filling of the containment

In BWRs, it is considered that the most reliable way to reach a long term safe stable state is to fill the containment up to at least the bottom of the reactor vessel with water. Water pumped into the upper drywell via the spray nozzles will wash out aerosols and, since it is cold, will also stop the steam pressure rise in the containment.

This can be achieved by connecting the independent fire fighting system to the containment spray. In one plant (TVO) provision is made to flood the containment up to the normal core upper level, requiring about 5000 m3 of water. The fire fighting system has two diesel motor driven pumps with pump heads about 1.0 MPa and capacities of about 0.1 m3/s per pump. The system can also be pressurised from external sources giving a high redundancy to the water filling function. This pumping capacity which enables the containment to be flooded to the appropriate level within 8 hours may not, however, be typical; for example, a proposed 0.045 m3/s diesel-driven pump at the Pilgrim plant would take over 29 hours to achieve the same objective.

When developing accident management strategies based on using water from the fire-fighting system, careful consideration must be given to whether recriticality of the corium could arise if the latter contained little or no suitable control rod material.

Application - PWRs

Similar considerations to those for BWRs considered above apply to PWRs. The cavity walls in PWRs generally act as the containment boundary and, to protect them from attack by hot debris, the cavity should be filled with water by the time of a possible vessel melt- through. How this is done may depend on the type of containment - one possible way is to use the spray system described in the previous section.

Another example is in an ice condenser containment. In the Loviisa PWR, the baskets have a large mass (typically about 1000 tons) of ice which should melt in almost all severe accidents (except containment bypass sequences). The melted ice will flood the cavity submerging the reactor pressure vessel in water up to the hot leg nozzles. Hence, no active systems are needed to fill the cavity. However, this is very design-dependent. In the Duke Power ice condenser plants the ice inventory is insufficient to flood the cavity and most of the Refuelling Water Storage tank has to be used to submerge the vessel; moreover, in some accident scenarios less than half the ice is expected to have melted by the time of vessel failure.

For reactors with low power density, heat losses through the vessel walls and cold legs are estimated to be sufficient to accommodate the small decay heat due to the low power density. It might be then possible to stabilise the core debris already in the lower plenum of the reactor vessel, if it is possible to provide water access to the pressure vessel outer surface.

The main drawback to this is that if the melt cannot be maintained in the reactor pressure vessel, reactor vessel failure and ejection of the debris to the water-filled cavity may result in a significant pressure pulse or steam explosion.

3.6 Hydrogen management techniques

Hydrogen management techniques are considered in greater detail in a companion paper to this entitled "Hydrogen Management Techniques in Containments" by the Task Group on Containment Accident Management [4]. This section thus summarises the current position.

Objective

Hydrogen can be generated in LWR plant in several ways, including

- the zircaloy-steam reaction at high clad temperatures
- the reaction of structural materials and galvanised surfaces with water and steam
- the molten core-concrete reaction
- radiolysis of water by fission products
- the high pressure melt ejection / direct containment heating phenomenon.

During a severe accident, the release of hydrogen to or its generation within the containment may result in the build-up of flammable concentrations which ignite on contact with sufficiently hot surfaces. Depending on the containment's free volume and the relative masses of hydrogen, oxygen and steam present in the atmosphere, such a burn could cause damaging overpressures. The goal is thus to prevent both early and late containment failure by hydrogen burns. Four issues have been given priority:

- To exclude the possibility of a global detonation or deflagration with the potential to reach failure-pressure of the containment

- To prevent local detonations which could cause missile generation

- To prevent high local concentrations of hydrogen

- To mitigate the consequences of local multiple burning which could cause high temperatures which might fail local equipment.

It is hoped to resolve these issues using a mixture of accident management techniques, for example by

limiting hydrogen production and its release, which in turn depends on

- ex-vessel coolability of core material
- limitation or termination of core-concrete interactions

limiting the build-up of pockets of high hydrogen concentration by

- deliberate ignition of flammable gas mixtures
- catalytic induced reactions
- venting of the atmosphere (see section 3.2)

preventing hydrogen burns by inerting the containment atmosphere with CO2 or N2. This is considered more fully in section 3.7 below.

Implementation

The question of limiting hydrogen production and its release is more properly a question of accident management before the containment is called upon to act as the final barrier preventing the release of fission products to the environment and so is not addressed here. However, the question of limiting hydrogen concentration is very much a matter of containment severe accident management.

A widely-proposed method of limiting hydrogen concentration is to recombine it with oxygen under controlled conditions and four different systems have been proposed:

- glow plug igniter
- catalytic igniter

- catalytic recombiner
- spark igniter.

Glow plug igniter

Glow plug igniters are similar to those used in diesel engines. They each need about 150 W of electrical power, and are operated manually from the control room. They can be turned on and off at will, and their operating life is very long. On the other hand their high energy consumption calls for a suitable power source to be available on demand. They can only function successfully in flammable atmospheres. Moreover, their installation requires a large number and length of cables and additional penetrations into the containment.

Catalytic igniter

There are two types of catalytic systems currently being studied. The first is a catalytic igniter in which the catalyst and its integral igniter wire system are accommodated in a metal housing for protection from the environment during normal reactor operation. The cover opens automatically when the setpoint temperature is exceeded by the action of springs liberated by a fuse link. The gas mixture containing hydrogen enters the housing. The catalyst recombines the hydrogen, the exothermic reaction causes the igniter element to become hot and eventually the gas surrounding the igniter element ignites when its ignition temperature is exceeded. The system is completely passive but requires a flammable atmosphere to function successfully.

Catalytic recombiner

The second type of catalytic system is based on a catalytic foil recombiner. Again, the system is passive so there is no need for external power or operator action; and the effectiveness of the catalytic reaction increases with temperature. It can operate over a very wide range of hydrogen concentrations and up to 90% steam and its operation increases convection in compartments, thereby reducing the potential for pockets of high concentrations of hydrogen to develop. However, it needs a large surface area to be effective and it must be protected against pressure transients. With careful attention being paid to the design and construction of the catalyst, it is possible to prevent potential poisoning by the containment atmosphere.

Spark igniter

This fourth type of ignition system triggers combustion of the hydrogen by generating a high energy spark. An enclosure protects all parts associated with spark generation against environmental impacts. The spark gap is located below the housing. Following a severe accident, rising pressure and/or temperature triggers the battery-operated electronic ignition system, which generates high-voltage pulses resulting in sparking between the electrodes. The batteries can generate six sparks per minute for more than five days. There is no need for external power or operator action.

The main problem, however, with the catalytic and the spark igniters is the setpoint for their triggering. For some severe accident scenarios the conditions in the containment can be very mild and nevertheless the production of hydrogen can be high (e.g. TMI). There is thus the temptation to choose a very low setpoint. By doing this for spark igniters there is a high probability of inadvertent operation which would deplete the batteries of the spark igniter and expose the catalyst of the catalytic igniter to the containment atmosphere, and this without the operator being aware of the loss of availability of the igniters. On the other hand, if the setpoint is high, there is a possibility that the igniters would not operate when needed.

Implementation

Ignition systems have been installed in several plants. Glow plugs have been fitted in some BWRs with Mark III containments and also in some PWRs with ice condensers. In some cases, only a limited number of glow plugs have been used; in such cases, for example in PWR ice condenser containments, the relatively large volume makes it essential that mixing fans or coolers are available to prevent local concentrations of hydrogen building up in areas not "seen" by individual igniters.

3.7 Pre/post inerting

Objective

Pre/post inerting the containment is another form of hydrogen management. The aim is to remove oxygen from the containment atmosphere so that a hydrogen burn cannot be sustained; moreover it is a means of mitigating the effects of a high pressure melt ejection / direct containment heating sequence where typically half the rapid pressure rise is due to exothermic oxidation. However, this beneficial effect is reduced since zirconium and steel in the core debris can react similarly with steam, albeit with a lower heat of reaction. The inerting gases considered are nitrogen and carbon dioxide.

Pre-inerting

LWRs may have pre-inerted containments which are inerted as part of their normal operating conditions and prior to any potential accident. The need to monitor continually the containment atmosphere for composition and pressure means that both the presence of unexpected concentrations of oxygen can be detected and eliminated, and the leak-tightness of the containment can be assured. The principal drawback is the inevitable restriction made on the ability of operating or maintenance staff to freely enter the containment.

Post-inerting

If the necessary equipment exists, the decision may be taken to inert the containment after an accident has begun to minimise the potential hazard due to a hydrogen burn. This is inherently less satisfactory than pre-inerting for several reasons:

- It requires plant operators to take a major irreversible decision while the accident is in progress;

- It calls for massive amounts of gaseous or liquid nitrogen or carbon dioxide to be delivered to the containment in a short space of time and hence for expensive and bulky equipment. The use of liquefied gases raises particular problems due to the high temperature differences impose on the equipment; and

- The containment must be vented to allow the oxygen to be purged, thereby potentially allowing the escape of any fission products or noble gases already in the containment atmosphere.

Implementation

All LWRs with inerted containments use the pre-inerted option with nitrogen as the inerting gas. At present, this has only been implemented mainly for BWRs, and then not universally. Moreover, for some BWRs it is proposed only to inert the wetwell. Sometimes the decision to inert the containment atmosphere has been taken because the calculated hydrogen concentration in a small containment free volume arising from design basis, and not severe core damage, accidents is sufficiently large as to cause some concern.

3.8 Fan coolers and other heat removal systems

Heat removal systems may be applied to containments as a way of reducing the containment pressure to and keeping it at a sufficiently low level. This is important in helping to prevent both early and late containment failure. Several of the systems previously discussed have this aim; here, two systems not included in this consideration are briefly described.

Fan coolers

The use of fan coolers in managing severe accidents is not often mentioned, although it is one possible way of reducing the containment pressure and this is their role in design-basis accidents. Indeed their large cooling capacity and rugged construction would suggest they should be used. The possible disadvantages are that they are operated from the control room and so might represent another item requiring operator action during an accident; that they can condense sufficient steam to enable a previously steam- inerted atmosphere containing hydrogen to become flammable; that the passages through their heat exchangers may become blocked by aerosols; or that they may be insufficiently qualified for severe accident conditions. On the other hand, provided a power source is available, they have a high probability of being operational after a severe accident. They are normally always in operation to maintain an acceptable environment in the containment and they receive a "start" confirmation signal when the safety injection signal is given, thereby avoiding the need for operator action in the short term. Moreover, the steam condensation rate is lower than that achieved with the sprays which allows greater flexibility for hydrogen control.

Containment external spray

If the containment structure has a sufficiently large surface area of a good conductor of heat such as steel, it may be possible to provide long-term coolability of the internal atmosphere (and thus prevent steam- induced overpressure) by directing external sprays on to it. It could also help to guarantee the long term residual heat removal from the containment. If the system can keep the containment intact, no radioactive release will occur to the environment (not even noble gases, as with filtered venting). The required cooling rate is low, typically about 3 MW and so the spray mass flow needed is relatively low. However, an external spray can condense steam only, i.e. it cannot relieve pressures caused by the generation of non-condensable gases. This could be a problem where basemat concrete contains significant quantities of carbonates.

4. Discussion and Conclusions

4.1 Summary

In section 3, various containment accident management techniques were reviewed, as were some of their advantages and disadvantages. This section discusses these techniques in greater detail and presents some conclusions based on current understanding. In some places, the advantages or drawbacks of a particular system are discussed only in outline. This is because there is a fuller treatment of the issues involved in the relevant part of section 3.

4.2 Filtered containment venting systems

The aim of these is to prevent overpressure failure of containment (and with it uncontrolled release of radioactivity in the containment atmosphere). This is achieved by venting in a controlled way to prevent pressures rising to failure levels, with the venting taking place through a filter to reduce the activity released to a much lower level than that which would occur if the containment failed.

General issues concerning filtered vents

The decision of whether to vent is taken according to established procedures and criteria (e.g. containment pressure exceeds design pressure). In some countries this is a matter for the operators while in others it is taken by the competent national authority.

Some additional parameters that may affect this decision are:

- the relative masses of hydrogen and steam in the containment atmosphere (venting may turn a non-flammable atmosphere into a flammable one);
- the amount of airborne radioactive substances in the containment (the effects of resuspension of material deposited on surfaces do not appear to have been considered);
- wind direction, weather and the degree of protection to the public.

The capability to terminate venting, and conditions under which venting should be terminated, is an important consideration in assessing venting efficacy as a containment accident management strategy.

A potential drawback with filtered venting systems is that there is a danger that in some cases its use could result in significant subatmospheric pressures were air and noncondensibles to be vented with steam and the remaining steam in the containment condensed by inadvertent use of sprays. If the containment cannot withstand the subatmospheric pressure, failure can be avoided if a suitable vacuum-breaker system were to be installed.

Another concern could be the transport of radioactive aerosols in the venting ducts; if significant deposition occurred at bends, valves or similar flow constrictions, the build-up of active material could hazard operator safety, alter the flow characteristics of the system and in extreme circumstances could cause it to malfunction either through heat loading or the accumulation of particulates.

Possible other drawbacks of the system may be:

- additional instrumentation is needed, which may be wrongly interpreted by operators;
- earlier release than warranted (perhaps even an avoidable release) due to bursting of the rupture disk; and
- operator intervention may be called for and may either not be implemented when needed or implemented when not needed.

Conclusion

The questions of additional cost and operator training are marginal compared with the cost of a plant. Indeed, the opportunity to involve operating staff with developing the necessary procedures tends to produce an enhanced awareness of safety issues and is thus beneficial. The other questions, apart from hydrogen can be resolved by the appropriate R&D and subsequent design of a venting system. The question of venting resulting in a more flammable containment atmosphere is one that has to be considered for each individual plant, but, given that the vent is open, may prove not to pose too serious a threat. The real question to be asked is, given that the pressure within the containment is increasing towards the building's design pressure and this increase cannot be controlled, whether it is better to vent with a minimum release of radioactivity or to face the possibility of failure of the containment and a major release.

4.3 Use of spent fuel ponds as scrubbing pools

This is an alternative way of achieving filtered venting of a containment. As such, it has similar advantages and drawbacks in general terms as that system. Compared with the standard filtered containment venting systems the use of fuel ponds external to the containment has the following advantages and drawbacks.

Advantages

- Use of existing facilities
- Reduced need for additional equipment
- High retention factor
- Large heat sink

Drawbacks

- The pool chamber and, perhaps, other adjoining areas may become highly contaminated and thus inaccessible when the system is put into operation.

- Hydrogen may be vented into compartments incapable of withstanding the effects of its combustion. This in turn may require the installation of additional mitigation systems.

- The effects of the dynamic loads of the steam condensation in and flow through the pool (chugging) and the spent fuel racks have to be analysed. However, this is not expected to be a problem due to the air content of the discharged flow.

- The pool chamber and (possibly) adjoining areas may become pressurised. The release path must be capable of limiting any such overpressures to an acceptable level.

- The water level may rise due to the condensation of steam in and vapour-gas discharge through the pool. This must not cause additional hazards.

- The efficiency of the pool in trapping fission products may be reduced as its temperature rises. It may also be affected by the nature of the flows within the pool.

Conclusion

This system is still under investigation and it is not yet possible to reach a firm conclusion as to its potential value.

4.4 Spray systems

The spray system in an LWR has a specific role in reducing containment pressure. As an accident management tool it is intended to be used as a way of filling the cavity to a pre-determined level to assist with core cooling and to perform a similar role to the cavity flooding considered below.

Advantages

- Pressure build-up by steam generation will be avoided, thereby gaining time for operator actions to restore long-term containment cooling

- Radioactive aerosols are removed from the containment atmosphere and dissolved in the water

- By gradually filling the cavity, core material can be cooled

Drawbacks

- For PWRs, hydrogen burns may occur if previously uncondensed steam has inerted a hydrogen-rich atmosphere
- The ability of the sprays to remove heat from the containment atmosphere will be impaired if it proves impossible to provide adequate cooling for the spray water.

Conclusion

The use of sprays, which is standard in design basis accidents, should be an important part of containment severe accident management.

4.5 Injection of water / cavity flooding

For BWRs, the injection of water is designed to protect the liner in the lower drywell against direct attack by molten corium. Operator intervention is required. Long term cavity flooding is viewed as the most effective means of ensuring that a molten core can be returned to a safe stable state. For PWRs with a low power density the injection of water into the region below and partially immersing the vessel may also prevent vessel failure.

Advantages

- Expected to prevent containment failure due to attack by molten core material

Drawbacks

- Requires additional plant, procedures and instrumentation
- Possibility of a steam explosion which could damage the containment
- Can be activated inadvertently during start-up or during normal operation, thereby involving unnecessary clean-up operations.

Conclusion

This question is still being studied. The effect of adding water to the containment is not fully understood in accident management and more R&D is needed in this area.

4.6 Hydrogen management techniques

Hydrogen control may be effected by igniters which deliberately burn the hydrogen at low concentrations. Four systems have been proposed.

Glow Plugs

Advantages

- Controllable by operators
- Reliable and robust

Drawbacks

- Not passive, substantial power supply and possibly operator action needed
- Additional installation needed
- Additional instrumentation and procedures needed
- Cannot operate in steam-inerted atmospheres

Catalytic Igniters

Advantages

- Passive operation - no power or operator action needed
- No new instrumentation needed

Drawbacks

- Not controllable
- Set point for automatic initiation is critical and difficult to determine
- Cannot operate in steam-inerted atmospheres

Catalytic Recombiner

Advantages

- Passive operation
- Operates over a wide range of hydrogen-steam concentrations

Drawbacks

- May become "poisoned" and so ineffective without careful design
- Needs a large surface area to be effective and hence must be protected from pressure transients
- Set point for automatic initiation is critical and difficult to determine

Spark Igniters

Advantages

- Semi-passive operation
- No new instrumentation or procedures needed

Drawbacks

- Battery operation
- Limited duration
- Not controllable
- Set point critical and difficult to determine

Conclusion

Hydrogen ignition systems have significant potential to reduce the consequences of an uncontrolled hydrogen burn. Their deployment is very plant- specific and may require additional plant such as guaranteed mixing systems to ensure that not pockets of flammable hydrogen can build up away from an ignition source. The inability of igniters to function in steam-inerted atmospheres suggests a need to combine their deployment with that of catalytic recombiners. This is currently under discussion.

4.7 Pre / post inerting

This is an alternative hydrogen management system whereby a hydrogen burn is prevented by removing the oxygen from the containment atmosphere. It also reduces the potential pressure rise should high pressure melt ejection followed by direct containment heating occur during a severe accident. The issue is still being evaluated, although it is used in some nuclear power plant.

Pre-inerting has additional advantages in that it provides information on the leak-tightness of the containment during normal operation and also prevents oxidation of metallic components within the containment. However, it has an adverse effect on maintenance work, especially if the latter is necessary but unplanned.

There are several potential problems associated with post-inerting. For example, it could be triggered in design basis accidents and, particularly if liquid nitrogen were to be used, turn them into severe accident situations. Moreover, the injection of gaseous nitrogen requires a large heat source and large diameter pipes etc. which present difficulties in both installing and operating the equipment. There are similar problems in using carbon dioxide.

Both pre- and post-inerting require a suitable venting system; while this could be a relatively straightforward mechanism in the former case, inerting the containment under accident conditions calls for equipment which would minimise the transfer of released fission products to the environment.

Conclusion

There appears to be little to be gained by inerting containments once a severe accident sequence has started. Pre-inerting containments can be beneficial both in terms of hydrogen control and in understanding the state of the containment atmosphere, providing the associated denial of free access to the containment is acceptable.

4.8 Fan Coolers and Other Heat Removal Systems

The explicit use of fan coolers in severe accident management does not generally appear to have been considered. The advantages are that they provide an additional source of cooling of and hence of lowering the pressure in the containment atmosphere; and that a well-mixed atmospheres less likely to contain hydrogen in detonable concentrations. The drawbacks include the need for a substantial power source; by condensing steam, an atmosphere inert to hydrogen burns may become capable of sustaining them; and there is a possibility of impaired function due to the build-up of aerosols.

An external spray may be effective as a way of preventing steam-induced overpressure if a sufficient surface area of high thermal conductivity material exists in the containment wall. It has the advantage of keeping the containment sealed - no venting is required. It has the disadvantage that permanent gases (e.g. H2, CO and CO2) are not affected; however, in specific cases this may not be a problem.

5. General Conclusions

This paper has reviewed several techniques of containment severe accident management. Some of these are already installed on some reactors, for example filtered containment vents, hydrogen igniters and pre- inerted containments. Other techniques are still being investigated, such as venting through spent fuel ponds. The question of whether to implement of these techniques can only be answered in terms of national regulatory requirements, the perceived benefit to be gained, and the practicability for a particular reactor. These considerations are beyond the scope of this paper.

Specific conclusions relating to particular techniques have been presented in section 4; they are summarised here.

Containment Venting

Filtered venting for containment is being implemented on both BWRs and PWRs. The perceived advantage is that it protects the containment from failing due to long-term overpressure, thereby enabling it to retain the bulk of the fission products while releasing essentially trivial amounts of radioactive material to the environment. However, the provision of such a system brings with it the possibility that it might operate or be operated when not required, leading to a possible release of radioactivity from an otherwise intact containment. This represents a possible additional risk. Whilst it is possible that filtered venting may, overall, reduce the risk from the operation of a plant, it is not possible to say that this will in general be true and a detailed and case-specific analysis would be needed.

Injection of Water / Cavity Flooding

These may prevent long-term containment failure due to attack on containment structures by molten core material released after core melt and vessel failure. They require additional plant and equipment and bring with them the possibility of steam explosions which may themselves damage the containment. A detailed case-specific analysis is needed to determine whether this is appropriate.

Hydrogen Management

Hydrogen burn is a threat to containment integrity which has resulted in the installation of igniters of various types in several reactor containments. How this is best done to meet the variety of possible challenges, including those of steam-inerted conditions, is currently being discussed.

Inerting does not have these disadvantages but has others, particularly the risk to the operators from entry into the containment and the difficulty of achieving uniform inerting levels throughout the containment. It is used in some BWRs.

Other Heat Removal Systems

Fan coolers have certain potential advantages since they are already installed in most containments. However, their successful operation as part of a severe accident management strategy has still to be determined.

An external spray system has potential advantages as an alternative to containment venting because it leaves the containment intact; it has potential disadvantages regarding the type of gases producing the overpressure threat. These questions are very design- specific.

Overall conclusions

The overall conclusion is that each of the currently proposed accident management strategies for the containment has both advantages and disadvantages. An evaluation is therefore needed to determine the benefit which may be derived from adopting a particular strategy. Systems such as containment venting (with or without the use of sprays) do appear to offer significant advantages provided that the scope for operator error can be reduced. Some systems such as hydrogen igniters are nearing the end of the development stage and look promising. Other concepts such as water-injection / cavity flooding and hydrogen mixing require much more development before a final verdict can be given.

There appears to be considerable merit in adopting several of these measures within the same plant as the field of operation of one generally addresses a problem ignored by another and so there is likely to be little mutual impact. However, this is not always so; for example the use of sprays while venting might lead to an unwelcome subatmospheric pressure in the containment. Moreover, when several systems are available, even though there may be little interaction between them, conflicts of priority may arise. Thus accident management strategies need to consider all the available options and the effect of potential interactions before they are implemented.

6. References

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Appendix 2

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(March 1992)

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ANNEX

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.