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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

IMPACT OF SHORT-TERM SEVERE ACCIDENT MANAGEMENT ACTIONS IN A LONG-TERM PERSPECTIVE

Final Report

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

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of 27 OECD Member countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its Member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

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

PWG4

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

CAM

The Task Group on Containment Aspects of Severe Accident Management (CAM) is a specialised extension of PWG4. Its main tasks are to exchange information, discuss results and programmes, write state-of-the-art reports, organise specialist workshops on containment accident management and on techniques to protect the containment and their implementation.

FOREWORD

The purpose of this short Technical Note, deliberately limited in scope, is to draw attention to potential long-term problems, important to utilities and regulatory authorities, arising from the way a severe accident would be managed during the first hours. Its objective is to encourage discussions on the safest - and maybe also most economical - way to manage a severe accident in the long term by not making the situation worse through inappropriate short-term actions, and on the identification of short-term actions likely to make long-term management easier and safer.

The Note is intended as a contribution to the knowledge base put at the disposal of Member countries through international collaboration. The scope of the work has been limited to a literature search. Useful further activities have been identified. However, there is no proposal, at this stage, for more detailed work to be undertaken under the auspices of the CSNI. Plant-specific applications would need to be developed by utilities.

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1. INTRODUCTION

The present systems for severe accident management are focused on mitigating the consequences of special severe accident phenomena and to reach a safe plant state. However, in the development of strategies and procedures for severe accident management, it is also important to consider the long-term perspective of accident management and especially to secure the safe state of the plant. The main reason for this is that certain short-term actions have an impact on the long-term scenario. Both positive and negative effects from short-term actions on the accident management in the long-term perspective have been included in this paper.

Short-term actions are accident management measures taken within about 24 hours after the initiating event. The purpose of short-term actions is to reach a stable status of the plant. The main goal in the long-term perspective is to maintain the reactor in a stable state and prevent uncontrolled releases of activity.

At the PWG4 meeting held on 25-26 September 1997, it was decided that a Technical Note should be written with the following two objectives:

- To identify and describe issues, where short-term actions have an impact on accident management in a long-term perspective.

- To identify future work on those issues to be used in the development of severe accident management strategies.

This Technical Note has been written by a group consisting of: V. Gustavsson, Swed Power, Vattenfall (Co-ordinator), J. Rohde, GRS and M. Vidard, EdF. It has been discussed at the meetings of PWG4's Task Group on Containment Aspects of Severe Accident Management (CAM).

2. PREVIOUS STUDIES

In Sweden a project has been conducted, where the impact from short-term actions on long-term accident management has been addressed. This is described in [1] and also briefly summarised in the following. The acronym of this project is FRIPP (**F**orsmark **Ri**nghals **P**ost- Accident **P**roject).

The main objectives of the project were:

- To get increased knowledge about the long-term scenario after a severe accident.

- To use the new knowledge to improve the short- term severe accident management strategies.

The following issues were investigated:

- Source terms and radiation

- Cooling capacity needed for the containment

- Production of hydrogen and oxygen by radiolysis

- Water chemistry in the containment

- System analysis
- Waste management
- Strategy to minimise environmental consequences

Two reference reactors were selected for the project; Forsmark 1, a BWR of ABB Atom design and Ringhals 3, a Westinghouse PWR.

The time interval studied in the project was from one week to five years after the initiating event. As a result of the work several issues were identified, where short-term actions are of importance for the long-term perspective.

The instructions and handbooks were improved by use of these results, both for the BWR and PWR, especially concerning water filling of the containment and water chemistry in the containment after a severe accident.

Another study where long-term considerations in severe accident management are included is [2], where the emphasis is on the following issues:

- Containment Spray
- Steam Generator Flooding
- Reactor Cavity Flooding
- Venting of Containment

An issue included in [2], but not in this report is containment flooding to prevent reactor vessel failure, often called in-vessel retention.

Part of the information presented in this paper comes from the Swedish project described above and from [2] and [3]. However, important contributions were also provided by GRS and EdF.

3. ISSUES WHERE SHORT-TERM ACTIONS HAVE A LONG-TERM IMPACT

3.1 Water Chemistry in the Containment

The water chemistry in the containment is important from two aspects:

- The pH value in the sump water has an impact on the release of volatile fission products.
- The corrosion rate in steel components is related to water chemistry.

In case of an accident leading to partial or total melting of the core, highly water-soluble chemical compounds such as CsI, CsOH or HI will be released to the containment. These compounds will tend to absorb water available in the containment atmosphere and form droplets composed of electrolyte solutions. These droplets will be removed from the containment atmosphere and lead to build-up of iodine and caesium in particular, in water pools and, to a lesser extent, on surfaces.

Amongst all materials, iodine, which first dissolves in water under the iodide ion form, is that with the highest propensity to form volatile species.

At low concentration, as could be expected during an accident, studies of the relationship between important aqueous iodine species show that a high H+ concentration (low pH) tends to increase the relative concentration of volatile molecular iodine, while low H+ concentration (high pH) tends to increase the relative concentration of ionic species (iodide and iodate). As radiolysis generates oxidising entities, these can oxidise the iodide ion to more volatile species: it is therefore important to maintain ambient conditions favouring the stabilisation of iodide ions, i.e. high pH.

Providing chemical additives with the potential for increasing pH in the containment at the very beginning of the accident appears very important to eliminate further concern related to volatile species release to the environment.

In FRIPP the water chemistry was investigated based on known quantities of material involved in chemical reactions in the containment without addition of any chemicals after the beginning of the accident. The acidity of the water in the containment was estimated assuming equilibrium conditions. For both BWR and PWR two different pH values were obtained depending on what chemical reactions dominate. The important conclusion is that the equilibrium pH value is less than 10, which is a recommended value to minimise corrosion of components in the containment.

Thus, it is recommended to add chemicals to the containment after a severe accident in order to minimise corrosion and iodine volatility. To be efficient, this action should be taken within a few days after the beginning of the accident. Also in the long-term phase the pH level in the containment water could be monitored and necessary actions taken to balance it to a desired value.

3.2 Cooling of the Containment

The containment can either be cooled passively by heat losses through the walls or actively by use of a cooling system. In any case, the cooling capacity must correspond to the decay power from the fuel debris.

The temperature in the containment should be limited to a level at which the loads against the containment, in particular the penetrations are tolerable and at which the corrosion of containment materials provides no significant hydrogen source. The effect of containment water temperature on hydrogen generation due to corrosion of zinc, in particular, is important and is discussed in more detail in Section 3.6.

Long-term cooling of the containment was one of the issues investigated in FRIPP. In this study it was shown that active cooling is needed during five years after the accident in Forsmark 1 and one year in Ringhals 3.

If the cooling is insufficient the temperature and pressure in the containment increase until the filtered venting system is activated. This will cause a controlled (small) release to the environment.

However, component failures in the cooling system cannot be excluded, and these failures could prove difficult to fix. Furthermore, the cooling systems available today have the disadvantage that contaminated water is recirculated outside the containment when these systems are used. Alternative solutions using a closed loop inside the containment and non contaminated water outside the containment could be contemplated where technically feasible, provided the cost is reasonable and if their implementation does not weaken the containment in terms of resistance and leak tightness.

Generally it is important as a short-term action to prepare the long-term cooling of the containment. Certainly the solutions will be plant-specific, but the issue of long-term cooling is important in any case.

3.3 Reactor Cavity Flooding

In case of an accident with core degradation, though the operators take action to try and limit melt progression by restoration of the water injection capability into the RCS, the main objective is to maintain containment integrity whatever the evolution of the accident is. If the situation were to degrade further, melt progression could result in vessel meltthrough, and, if core debris were not in a coolable geometry, to basemat attack and, ultimately, loss of containment integrity resulting from basemat meltthrough. This could lead to an interaction of the molten material with the subsoil and long-term contamination of the ground water.

Though one cannot absolutely guarantee that flooding the reactor pit would actually provide for full debris cooling, it is nevertheless obvious that such a mitigative action would at least limit basemat attack and provide for significant if not complete fission product scrubbing in the pool. Moreover, as steaming is to be expected, flooding has also the potential for preventing the formation of highly volatile and health damaging compounds such as $RuO_{4,}$ compounds resulting from the oxidation of low volatile fission products under a dry atmosphere.

Concerning the timing, cavity flooding should be started early in the accident, i.e. after the core has started to melt. The reason for such an early decision is that, once the core has started to melt, accident progression becomes very difficult to assess, in particular vessel meltthrough. Experimental evidence tending to show that achieving debris coolability is easier through fragmenting corium flowing in a water pool than through flooding a pre-existing corium layer, early action is hence justified. Moreover, potential advantages of such early flooding outweigh by far, for some types of containments, the risks associated with potential drawbacks in case of vessel failure, in particular steam explosions.

Finally, one has to decide which water level fits better with severe accident management objectives, and decide what could be done, or is possible, depending on plant layout. Once it has been decided that the cavity should not be leaktight, water will flow into the cavity, and layout considerations will in fact govern the maximum possible level in the cavity.

3.4 Steam Generator Flooding

Steam Generator Tube Integrity is of utmost importance in case of an accident as tube rupture has the potential for breaching simultaneously two barriers, the Reactor Coolant System first and then the Containment.

Looking at accident progression, a leak from the Reactor Coolant System to the Steam Generator secondary side would degrade the decay heat removal capability, at least in the early phase of an accident, and put more burden on the operator, who would have to manage an extremely complex situation, as well as on other important decay heat removal systems thus increasing the risk of further degradation.

Moreover, a large amount of water in the Steam Generator is also beneficial for fission product scrubbing in case of tube break.

Objectives for accident management thus are:

- First to prevent consequential tube breaks
- Second to provide for fission product scrubbing in case of pre-existing or consequential breaks

Secondary Water Inventory in the Steam Generators as well as Storage Tanks Inventory should be continuously monitored. Steam Generators should be refilled whenever possible to:

- Provide a reliable means for decay heat removal from the primary system
- Prevent creep failure of the tubes
- Scrub fission products in case of leak from the primary to the secondary system

In any case, monitoring of the pressure difference between the primary and secondary system is recommended to limit negative break flows and thus minimise the injection of potentially non borated water into the RCS.

3.5 Leakage of Contaminated Water from the Containment Sump

After a severe accident the containment will be filled with highly contaminated water and a radioactive gas mixture. It is important to minimise the leakage of water as well as gases from the containment for the following two reasons. Firstly the radiation exposure to the staff at the plant should be low. Secondly the environmental consequences should be minimised.

In FRIPP [1] the water leakage from the containment was estimated and recommendations were given how this leakage should be minimised. Obviously it is very difficult to estimate water leakage from the containment in the long-term perspective after a severe accident. Degradation of penetrations due to radiation and corrosion will probably cause an increased leak rate in the long run. On the other hand it should be possible to take countermeasures to reduce the leakage.

The following recommendations were given to reduce the liquid leakage from the containment:

- Investigate how systems in connection with the containment can be isolated or pressurised
- If a circuit for active cooling starts to leak, isolate it and start an alternative circuit
- Keep pressure low in the containment

In the FRIPP study it was assumed that the containment is filled with water up to the upper core level in the reactor vessel. A lower water level, close to the bottom of the reactor vessel, is recommended in [1] mainly because it should give a lower leakage of water from the containment.

In a long-term perspective also some fraction of the containment atmosphere will leak. However, it is expected that gas leakage will cause fewer problems than leakage of active water. To reduce gas leakage it is important to keep the containment cooled at a low pressure.

3.6. The Hydrogen Issue

In a severe accident large amounts of hydrogen are produced by metal-water reactions. In a long time perspective hydrogen and oxygen are also produced by radiolysis in the containment sump. The amount is dependent on the sump water conditions and cannot be simply calculated. Beside the long-term hydrogen accumulation in the containment atmosphere, special attention should be drawn to oxygen generation. By this an initially inerted status could be lost. Therefore, specific control of oxygen is recommended in such a case.

A hydrogen deflagration, started by igniters, hot gases or other ignition sources might cause local damage on electrical equipment and instrumentation, which otherwise could be of use in a later stage of the accident.

Another aspect of hydrogen deflagration and recombination by Passive Auto-catalytic Recombiners (PARs) is that a large portion of the oxygen in the containment is consumed. This reduces in a positive way long-term corrosion.

Hydrogen may be produced in the long-term scenario also by corrosion of metal surfaces in the containment. For instance, zinc and aluminium exist in large quantities in some containments. In the worst conditions, i. e. with borated water at high temperature, corrosion of zinc, aluminium and other metals could be a source of hydrogen of the same order of magnitude as radiolysis. This is described in [3]. For example in borated water with pH=9, the hydrogen production rate is about a factor 100 higher at 110^{o} C compared to 90 ^{o}C.

3.7 Containment Venting

Containment venting is recommended to prevent slow over-pressurisation of the containment. During containment venting the amount of non-condensable gases in the containment is reduced. If the containment is then cooled, the pressure will decrease by steam condensation. Under certain circumstances, the pressure in the containment could reach sub-atmospheric conditions. Such conditions are of special interest for steel shell containments. Special attention should be drawn on specific conditions to prevent such conditions.

A possible effect of venting the containment in case of a severe accident is an increased release of fission products due to sump water evaporation. In addition, sump water evaporation decreases the depressurisation rate.

3.8. Containment Spray

The goal of the accident management strategy is to restore stable cooling of a damaged core and to maintain the integrity of the containment. As soon as possible during a severe accident, water shall be supplied to the containment by use of the spray system. This has the following positive effects:

- Pressure build-up in the containment is reduced.
- The core debris could be cooled.
- Radioactive aerosols are washed out from the containment atmosphere.
- Enhances mixing of the containment atmosphere.

However, there are also some negative effects related to the use of containment spray, first the inerting effect of steam on formation of combustible gas mixture is reduced. At a late stage in the accident spray is used in a recirculation mode. This causes redistribution of fission products and speeds up corrosion in the containment. Moreover, addition of boric acid to decrease the reactivity gives increased corrosion and hydrogen production.

A positive effect of spray is that activity is washed out from the containment atmosphere. However, a drawback is that when the activity in the sump increases the hydrogen production will increase, due to extended sump water radiolysis.

4. SUMMARY AND CONCLUSIONS

Up to now, the development of strategies for severe accident management has concentrated on reaching a stabilised and controlled plant state.

However, a number of issues have been identified, where short-term actions might have an impact on the accident management in a long-term perspective to maintain a stable state.

For some of those issues a short-term action has a negative impact in the long run while for others the opposite is the case. An example where a short-term action might have mixed effects in the long run is the addition of chemicals to the containment to obtain desirable chemical conditions.

Most of the issues discussed in Section 3 above are of a general nature and relevant for all reactor types. It is clear, though, that the importance of these issues and also what should be done to improve both short-term and long-term accident management is plant-specific.

Present accident management strategies can be improved by carefully investigating the influence of short-term actions on the situation in a long-term perspective.

Even if this development is plant-specific, a sufficient knowledge of severe accident phenomena is the basis for this work.

5. FUTURE WORK

In this section suggestions for future work are described (without specifying in which framework such work should be undertaken). The following objectives are proposed:

- Give a more comprehensive summary of existing knowledge about the issues described in Section 3 above.

- Draw conclusions concerning severe accident management from existing knowledge.

- Identify areas where more research is needed as a basis for further development of severe accident management.

- Comment on possible severe accident management impact on the conditions at the time of reactor dismantling.

In this report a number of issues where short-term actions have an impact on long-term severe accident management have been described briefly. This work has been deliberately limited in scope and effort. With more time and resources, a more comprehensive description can be given.

As a next step in future work, conclusions regarding the effect of short-term actions on the scenario in the long-term should be drawn. This should not only be done in a general way, but also include examples with plant-specific issues.

Probably it will be an outcome of future work that, in certain areas, more knowledge is needed in order to develop severe accident management strategies concerning issues where short-term actions have an impact on the long-term scenario. As part of future work it is therefore suggested that those areas are listed and specific issues, where there is a lack of knowledge, identified.

The possible impact of short-term severe accident management actions on waste management and radiation protection problems at the time of reactor dismantling should be considered as part of future work.

6. REFERENCES

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