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Severe Accidents Management in PWRs

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Abstract

This paper identifies severe accident management strategies developed for current evolutionary reactors and deals with implementation of some measures to existing nuclear power plants, which do not include severe accident mitigation measures in their original design projects.

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Keywords: severe accident; severe accident management; mitigation measures

1. Introduction

In case of pressurized water reactors, severe accidents are the accidents associated with significant core damage. The phenomena occurring during severe accidents are as follows:

- Cladding damage
- Fuel melting and core degradation
- Fuel-coolant interaction in the reactor vessel
- High-pressure core melt ejection from the reactor vessel
- Slow reactor vessel melting through
- Hydrogen combustion
- Containment overpressurization
- Core-concrete interaction
- Containment by-pass

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Cladding damage is caused by excessive heat up and pressure. These two factors acting on cladding can lead to loss of its integrity with gap release of fission products and also fuel fragmentation can occur in case of high burn-up. Fission products accumulated in the fuel matrix release if the core damage is not terminated and once fuel melting has started. The possible fuel-coolant interaction can lead to steam explosion with potential generation of missiles. High-pressure core melt ejection from the reactor vessel is followed by direct containment heating. It leads to rapid increase of containment temperature and pressure, challenging the containment integrity. If the high-pressure core melt injection is not the case, the reactor vessel will be slowly melt through with a possibility of ex-vessel steam explosion and generation of missiles. Another severe accident phenomenon is hydrogen combustion. The hydrogen deflagration or detonation could lead to fast loading with possible early containment failure due to loss of its integrity. Containment overpressurization can be caused by generation of steam or non-condensable gases from decomposition of the containment concrete and combustion of other combustible gases. Another possible loss of containment integrity is due to basement melt-through in case of core-concrete interaction. Containment bypass is an event in which the function of the containment as the final barrier is lost without its failure [3].

Consideration of severe accidents currently represents the main trend in design of new reactors and also in safety upgrading of existing nuclear power plants. It requires addressing a number of specific challenges to barriers against releases of radioactive substances into the environments. In accordance with defense in depth philosophy, occurrence of severe accidents shall be considered in the plant design independently of any measures implemented for prevention of such accidents. A set of measures and actions taken during the evolution of a severe accident are called severe accident management and its objectives are to:

- Terminate the progress of core damage once it has started
- Maintain the capability of the containment as long as possible
- Minimize on-site and off-site releases
- Return the plant to a controlled safe state

Severe accident management should cover all states of plant operation as well as selected external events, such as fires, floods, earthquakes and extreme weather conditions that could damage significant part of the plant [1,6].

The current trend in nuclear industry is to implement new safety requirements to existing reactors and simultaneously extend their operation significantly beyond the originally projected life time. Nevertheless implementation of severe mitigation strategy in existing nuclear power plant is a complicated task due to a several basic principle, which should be taken into account during development of the strategy. Selected severe accident mitigation strategy shall be fully in compliance with the relevant legislations and its technical and organization means shall be reasonably applicable, sufficiently proven in similar facility and feasible for implementation in short period to avoid production losses due to the shutdown [2]

2. Identification of severe accident management strategies

2.1. Depressurization of the primary circuit

Depressurization of the primary circuit is a strategy which provides preventive and as well as mitigative effect. It initiates primary system feed and bleed procedure and use of low pressure water sources to avoid the core melt. It also ensures that induced high-pressure core melt ejection or direct containment heating cannot lead to containment failure. The depressurization strategy is well demonstrated and it is commonly implemented in severe accident management in modern power plants by a dedicated depressurization station or by opening pressurizer relief valve. In existing nuclear power plants the reactor coolant system depressurization strategy could be relatively well adopted and implemented within their safety upgrading programs (e.g. by means of the pressurizer power operated relief valve if capacity of the valve is sufficient to depressurize the primary system below before the bottom head could fail) [2,7].

2.2. In-vessel retention of molten corium

The re-establishment of water injection into the reactor pressure vessel can stop the progression of core degradation and avoid reactor vessel failure. Nevertheless the injection could also cause several potentially negative effects, depending on time when it is initiated. However, it can be concluded that positive cooling effects prevail over potential negative ones and it is recommended to restart water injection into the reactor pressure vessel as soon as possible from any available borated water source. This strategy is ensured by emergency core cooling system recoveries or a modified emergency core cooling function [2,7].

2.3. In-vessel retention of molten corium through external cooling of the reactor pressure vessel

External cooling of the reactor pressure vessel is ensured by the cavity filled by water. The reactor pressure vessel is submerged in water and the decay heat from the corium pool is transferred through the vessel wall into the water-filled cavity. Flooding of the cavity should be done passively, using condenser as a source of water. This strategy for halting the progress of the severe accident is used in design of modern reactors and it has already been implemented in several existing power plants in order to proceed their safety upgrading. Nevertheless implementation of this strategy requires significant hardware modifications, because the following issues must be addressed:

- Coolant inventory required and available for reactor cavity flooding
- Time window available for cavity flooding as required for successful in-vessel retention
- Critical heat flux on the external vessel surface
- Behavior of molten corium inside the vessel
- Thermal-hydraulic conditions of coolant in the reactor cavity determining heat removal, boric acid mixing steam venting from the cavity
- Impact of molten corium on the reactor pressure vessel wall and resistance of the vessel against failure [2,7].

2.4. Ex-vessel cooling of molten corium or core debris

There are a number of strategies in new designs of nuclear power plants to mitigate ex-vessel phenomena, such as modified cavity configuration or installation of core catcher to improve corium spreading. The current focus is on the issue of corium release into a dry or a wet cavity. Water would be obviously required to enhance corium cooling also in originally dry cavity, but conditions for coolability of corium in the reactor cavity and its pressurization due to possible steam explosions are still under study. Due to the complexity of ex-vessel phenomena and significant hardware modification needs for implementation of measures to mitigate the phenomena, in-vessel corium retention should be given a preference in existing designs [2,7].

2.5. Containment overpressure protection

Under certain conditions pressure buildup inside the containment during a core melt accident may exceed the containment design pressure. The containment could possibly fail from overpressure if there are no dedicated measures for the containment overpressure protection. A filtered venting or spraying of the containment atmosphere can prevent such a failure. The filtered venting is primary used to overpressure protection, but it can significantly reduce also source term to the environment.. In general, the filtered venting equipment are expensive, complex and large and in existing designs it may be therefore advantageous to use for the given objective ventilation systems with appropriate modifications. In the case of source term reduction, it seems more appropriate to use containment spraying than forced venting of the containment atmosphere with very large required capacity of filters [2,7].

2.6. Hydrogen mitigation

Hydrogen combustion is very complicated issue, because it may occur during the early part of the accidents. The containment vulnerability mainly depends on the low design pressure, the shape and generally bed conditions for internal mixing of the containment atmosphere. The new nuclear power plants take into account these factors in their design projects in order to reduce the hydrogen mitigation as much as possible. The current focus of hydrogen combustion research is on the issue of transition to detonation and for what geometrical conditions and hydrogen concentrations this phenomenon can occur.

There are three hydrogen control strategies have been found as the more effective and applicable also in existing designs:

- Catalytic recombiners
- Combination of CO2 inerting with recombiners
- Combination of severe accident spray, igniters and upgraded recombiners

The most promising option seems to be combination of combination of passive autocatalytic recombiners and igniters. Another feasible but more expensive option is intertization of the containment atmosphere. The both should satisfy the requirements to avoid hydrogen risk, but it is obvious that the choice of appropriate strategy mainly depends on a given containment[2,7].

The global state of implementation of severe accident mitigation strategies shows that this trend is broadened worldwide and implementation into operation of existing plants is practiced even if this action is not formally required by the regulatory body. The highest priority in worldwide practice is given to fast reactor coolant systems depressurization, use of passive autocatalytic recombiners and in-vessel retention strategy as an efficient way for halting severe accident and reduction of possible consequences [4, 5, 7, 8].

4. Acceptance criteria for severe accidents

The acceptance criteria addressing severe accidents shall be specified in national legislation or any guidance on applicability of design basis criteria to severe accidents shall be available. In general, besides probabilistic acceptance criteria, deterministic limitation of radiological consequences of severe accidents is the main criterion. There are three objectives specified in EUR related to radiological impact on the public:

- Minimal emergency protection action beyond 800 m from the reactor during releases from the containment (criterion: 50 mSv effective dose)
- No delayed action at any time beyond about 3 km from the reactor (criterion: 30 mSv effective dose)
- No long term action at any distance beyond 800 m from the reactor (criterion: 100 mSv effective dose)

In addition, restrictions on the consumption of foodstuff and crops shall be limited in terms of timescale and ground area.

The quantitative dose targets for an individual from external radiation and simultaneous intake of radioactive materials can be obtained by using EUR values as guidance. The dose targets are set up as follows:

- For emergency protection actions effective dose < 50 mSv beyond the exclusion zone
- For delayed actions effective dose < 30 mSv beyond the exclusion zone
- For long term actions effective dose < 100 mSv beyond the exclusion zone

In addition in compliance with EUR it was required to address the long-term effects of the accident by limiting releases of Cs 137 (which is the most significant radioisotope for long-term effects) to 100 TBq.

The radiological design targets can only be met if the containment integrity is ensured (in addition to actions towards minimization of containment releases and reduction of the in-containment source term). Neither early nor late loss of containment integrity is accepted with sufficiently high probability. Therefore, special design targets were established for ensuring the containment integrity and they are recommended to use also for safety upgrading of existing units. The design targets take into account containment integrity acceptance criterion (maximum internal overpressure), reactor coolant system pressure, coolability of molten corium, survivability of the equipment important for the containment performance, etc [2,8].

5. Effect of severe accident management measures on radiological consequences

A study has been performed for the nuclear reactor system WWER/ V 320. The reactor is originally projected with a simple containment, but the study considers that it is additionally equipped with the severe accident mitigation measures as follows :

- fast reactor coolant systems depressurization,
- passive autocatalytic recombiners for hydrogen management,
- reactor cavity flooding for halting accident progression, special ventilation system surrounding the containment.

This analysis is related to the large LOCA accident with complete loss of all power sources leading to a complete loss of all active emergency cooling system. The reactor system is analyzed during the first 24 hours of the accident (analyzed by Melcor 1.8.5). From the trend of pressure in containment it can be concluded that the sufficient reserve time is demonstrated until the containment spray system has been restored. The containment integrity is ensured. The investigation of release from containment leakage has been done according to the EUR document as guidance. The analysis results show that radiological impact of this accident is in compliance with acceptance criteria specified in EUR. [2].

6. Conclusion

All current evolutionary nuclear power plants are equipped with dedicated systems for severe accident management allowing reaching safety objectives. The means are following:

- The reactor is equipped either with a single containment with a shielding wall, or with a double containment with a thin or thick secondary containment.
- Depressurization of the reactor coolant system is made either by a dedicated depressurization station or by opening pressurizer relief valve.
- Molten corium stabilization is either in vessel by flooding the reactor cavity, or ex-vessel, in the core catcher or in corium spreading compartment.
- Hydrogen management is ensured either by igniters, by combination of igniters and recombiners, or by recombiners only.
- Long term containment heat removal is ensured either fully passively, or actively, by means of a dedicated containment spray system.
- None of the designs uses filtered venting of the containment as an ultimate overpressure protection.
- Initiation of actions can either be passive or active by the operator action.

Severe accident mitigation measures were not included in the original design of existing nuclear power plants. The current trend is to eliminate this design deficiency within their safety upgrading. Although the safety and cost effective severe accident management strategy for existing reactors in compliance with the new safety requirements is a complicated issue, it can be concluded that some of the measures developed for new reactors are also applicable for existing designs.

The preliminary analyses of specific progress of large LOCA accident with complete loss of all power sources leading to a complete loss of all active emergency cooling system at WWER/ V 320 has been performed. The reactor is originally projected with a simple containment, but the reactor is additionally equipped with the severe accident mitigation measures.

The analysis showed that the implementation of these feasible measures is able to reduce radiological impact of severe accidents in compliance with acceptance criteria specified in EUR. Nevertheless more detailed safety analyses are still needed [2].

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