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MAIN FEATURES OF THE CORE MELT STABILIZATION SYSTEM OF THE EUROPEAN PRESSURIZED WATER REACTOR (EPR)

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ABSTRACT

For the European Pressurized Water Reactor (EPR) a fourth level of defense-in-depth has been introduced to limit the consequences of a postulated severe accident with core melting. This requires to strengthen the containment and to implement measures which can either prevent high loads on the containment structures or mitigate effects of severe accidents in a way to maintain the containment integrity. According to the Technical Guidelines released by French and German Licensing Authorities for the EPR early containment failure caused by High Pressure Melt Ejection (HPME), large steam explosion and hydrogen detonation are to be "practically eliminated". Low pressure RPV melt-through, hydrogen mitigation and containment overpressure prevention have to be coped with by specific design measures.

The paper describes the design measures provided to prevent molten corium interaction with the basemat concrete and its consecutive melt-through. The provisions foreseen are temporary retention of the corium within the reactor pit, spreading and cooling within a core catcher located in a compartment lateral to the pit. The cooling and stabilization of the corium is completely performed by passive means. Complete solidification of the melt is achieved after a few days.

The concept of Severe Accident mitigation for the EPR has a sound R&D basis with respect to component qualification, models and code validation. The provided measures lead to an overall safety level which is unique for large evolutionary Pressurized Water Reactors.

INTRODUCTION

Since the European Pressurized Water Reactor (EPR) relies on the proven designs and technologies implemented in the French N4 and German Konvoi PWR plants, it also relies on the defense-in-depth approaches realized in those designs. The objective for the EPR was to introduce improvements on all defense levels in an evolutionary way and thereby to decrease the probability of the occurrence of a severe accident with partial or even complete melting of the core. Beyond that, the Safety Authorities in France and Germany have required that measures should be taken at the design stage to limit the consequences of severe accidents involving complete core meltdown. These requirements stipulate that there must not be a need for evacuation of the surrounding population except in the immediate vicinity of the NPP site, as well as for long-term restrictions with regard to the consumption of locally grown food.

To fulfill this requirement, the EPR design does introduce, beyond the evolutionary improvements, an additional fourth level of defense, namely the mitigation of the consequences of severe core damage by introducing measures and layout features for severe accident mitigation and by strengthening the confinement function [1].

Among the relevant severe accident issues which have to be considered, the stabilization of the core melt within the containment is one of the most challenging tasks for which design measures have to be provided.

REQUIREMENTS FROM TECHNICAL GUIDELINES

The Technical Guidelines (TG) for future Pressurized Water Reactors in Europe were released in November 2000. They underline that a significant improvement of the safety of the next generation of nuclear power plants at the design stage is necessary, compared to existing plants. They state that although the search for improvement is a permanent concern in the field of safety, the necessity of a significant step at the design stage clearly derives from better consideration of the problems related to severe accidents, not only in the short term but also in the long term, due to the potential contamination of large areas by long life radio-nuclides like caesium. The TG require that situations with core melt which would lead to large early releases have to be "practically eliminated;" if they cannot be considered as physically impossible, design provisions have to be taken to design them out. Such situations are as follows:

- High pressure core melt sequences
- Direct containment heating
- Global hydrogen detonation

- In-vessel and ex-vessel steam explosions threatening the containment integrity

Low pressure core melt sequences have to be dealt with, so that the associated maximum conceivable releases would necessitate only very limited protective measures in area and in time for the public. These situations are:

- Hydrogen control
- Corium stabilization
- Prevention of containment overpressure

The safety demonstration has to be achieved in a deterministic way, supplemented by probabilistic methods and appropriate research and development work.

DESCRIPTION OF THE EPR CORE MELT STABILIZATION SYSTEM

For the stabilization and long-term cooling of the molten core, the EPR relies on an ex-vessel strategy, which implies the spreading of the molten core on a large area with subsequent flooding and quenching. The resulting, high surface-to-volume ratio allows an effective cooling of the spread melt, even without crediting superficial fragmentation.

Melt relocation into the core catcher is promoted by a preceding temporary retention of the melt in the pit, with the admixture of sacrificial concrete. This results in an accumulation and pre-conditioning and enhanced the ability of the melt to spread.

The described ex-vessel solution has been favored against In-Vessel Retention (IVR) because of: (i) the too low margins of IVR at the high power rating of the EPR and (ii) the risk of a highly energetic steam explosion in case of IVR failure. The latter results in an increase in the probability of early containment failure with related negative radiological consequences that compare unfavorably with the achievable gain from the avoidance of late basemat melt-through.

GOALS AND PRINCIPLES FOR SELECION OF MECHANICAL DESIGN MEASURES

The measures to be implemented to generate states with well-defined conditions are selected according to the following priorities:

1. Prevention of inadmissible events and conditions
2. Minimization of effects and loads

The provided design measures which lead to the intended specific conditions and which are implemented as mitigation measures are selected under consideration of the following principles:

- Separation of function
- Use of passive means to appropriately consider the plant state in case of severe accidents
- Simple and robust design

PRINCIPAL FEATURES OF THE EPR MELT RETENTION AND STABILIZATION CONCEPT

The severe accident starts after all emergency measures have failed to maintain the core in a cooled and coolable configuration. The course of the disintegration of the core depends on the accident scenario and involves a significant uncertainty. Similarly high uncertainties are associated with the relocation of the melt into the lower head and finally with the failure of the RPV and the subsequent release of the melt. The general target for the choice of the concept has therefore been to:

- ensure the independence of the melt stabilization measures from these uncertainties
- protect the retention device from the not-well-quantifiable loads during RPV failure.

In the existing EPR concept this is achieved by placing the core catcher in a dedicated lateral spreading compartment, see Fig. 1.

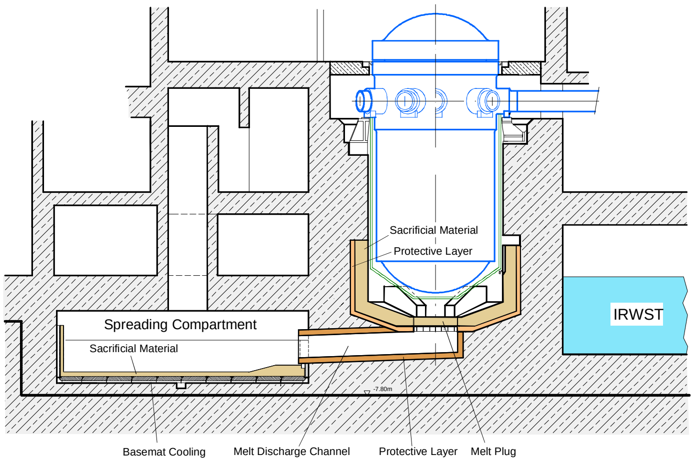

Fig. 1: Vertical section through the lower part of the EPR containment, showing the main components of the melt stabilization system

The related separation of functions between reactor pit and core catcher allows a robust design of the pit, so its bottom and walls are covered with a thick layer of concrete. The slow destruction of this sacrificial concrete layer does further provide an effective way to accumulate the melt before spreading. The admixture of concrete decomposition products results in a unification of the spectrum of melt states and in and an increased predictability of its properties.

The connection between pit and the spreading compartment is normally locked and will only be opened by the melt in case of a severe accident. This separation not only protects the core-catcher from loads related to RPV failure. Also an unintended flooding of the core catcher during power operation can not challenge the safety of the plant.

As a consequence of the uncoupling between operational components/systems and the provisions for severe accident mitigation, power operation and design-basis mitigation (including all related procedures) remain unaffected by the introduction of a core catcher.

TEMPORARY MELT RETENTION IN THE REACTOR PIT

The reactor pit is designed to withstand the loads resulting from a failure of the RPV under an internal pressure of at least 20 bar. These loads include melt jets and the mechanical impact of the detached lower head. The latter is absorbed by dedicated structures, located around the center of the pit. These structures also protect the melt plug at the entrance of the transfer channel between pit and spreading compartment, see Fig. 1.

It is ensured by design that at the time of release of the melt from the RPV, the reactor pit is completely dry. In addition, the probability of a late injection of water into the RPV during the period of melt release and temporary retention, is very low. This is due to the fact that (i) passive water supply systems can be assumed to be activated during the preceding depressurization of the primary circuit, while active systems are unlikely to be recovered, as their persistent unavailability had been a precondition for entering the severe accident in the first place.

The temporary retention and resulting accumulation of the melt is achieved by the sacrificial concrete layer provided on the inside of the pit, as well as by the elimination of melt escape-paths, other than through the transfer channel at the bottom. The length of the retention period is determined by the time needed to ablate the sacrificial layer and to thermally destroy the melt plug that locks the entrance of this channel.

The sacrificial concrete layer is backed-up by a cylindrical shielding consisting of refractory material, see Fig. 1. It confines the melt in radial and axial direction and can protect the RPV support structure in case the sacrificial concrete will be locally penetrated. The properties of the used refractory material are well known from numerous technological application. Its thermal mechanical stability against melt attack was also proven by dedicated experiments, e.g. in the CORESA project [2,3].

The analysis of temporary retention has revealed a favorable self-adjusting characteristic. It results from the fact that the melt - to ablate through a layer of defined thickness - must also generate a defined total amount of decay heat. A lower mass of initially released melt, or a lower decay heat level, will therefore result in correspondingly longer retention times, or vice versa. This guarantees an effective accumulation independent of the melt release sequence and of the time of initial RPV failure. In Fig. 2 the conditions of the melt for selected melt release cases which correspond to different scenarios are depicted. The figure shows that the amount of sacrificial concrete provided within the pit dominates and unifies the spectrum of melt states (composition, temperature) at the time of melt plug failure. The denomination assigned to the columns has the following meaning: the number (%) is the melt amount discharged from the RPV with the first pour, the first character indicates an early (E) or late (L) release of melt, the second character indicates a mixed (M) or layered (L) mode of the oxidic and metallic melt within the pit.

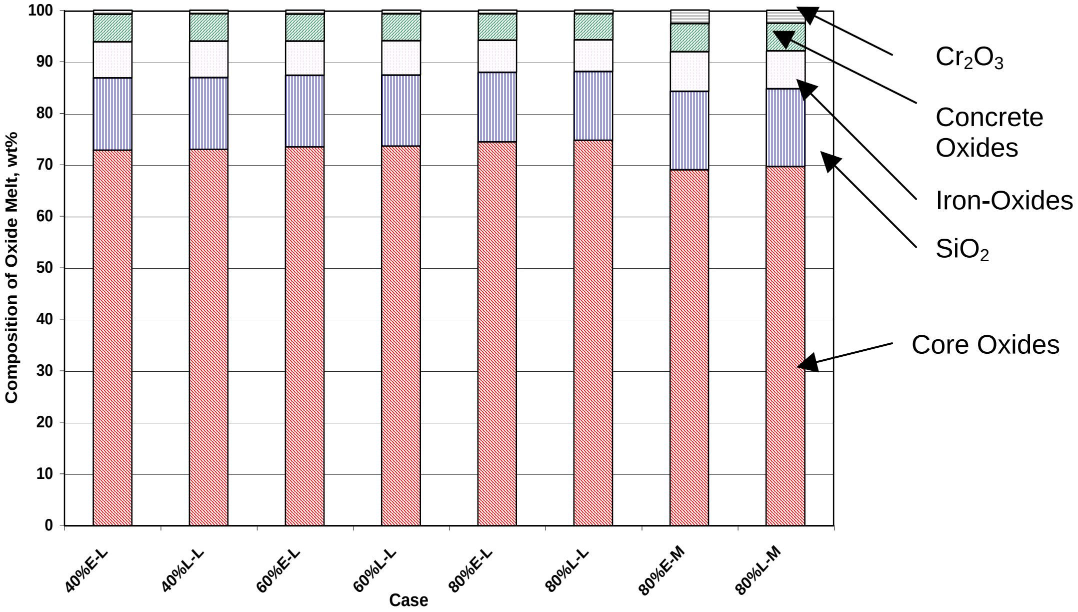

Fig. 2: Composition of the oxidic melt for selected melt release cases at the time of melt plug failure

This independence is further amplified by the fact that - during Molten Corium Concrete Interaction (MCCI) in the pit - the disintegrating core, the RPV, the sacrificial concrete, and the molten pool form a coupled, almost adiabatic system, as the residual RPV is not only heated from inside, but also by thermal radiation from the surface of the molten pool. Due to the effective gas-induced mixing within this pool, the upward directed radiant heat flux is comparable to that into the surrounding concrete. As a consequence, the heat-up of the RPV– under the expected dry conditions - is always coupled with the progress of concrete ablation. The corresponding MCCI analysis, which is validated by appropriate experiments, illustrates that for the given sacrificial concrete thickness of 50 cm, the lower head of the RPV will always fail long before the end of the retention period. The process of melt accumulation is therefore widely independent of the considered accident sequence.

MELT SPREADING

At the end of the retention phase, the progressing melt will penetrate the melt plug that closes the entrance of the transfer channel. The plug consists of a layer of sacrificial concrete at the top and a metallic support structure (the so-called “gate”) below. The latter carries the locking mechanism that holds the plug in position during normal operation. Lock and support structure are designed against 20 bar internal pressure, which corresponds to a total weight acting on the gate of more than 400 t. During shut-down, the plug can be removed through the transfer channel to allow access to the outside of the RPV for in-service inspection.

After melt contact, the gate can only loose heat by emitting thermal radiation into the transfer channel. However, as the walls of this channel consist of refractory material of low thermal conductivity the period during which the gate can sustain the weight of the melt is limited Though the initial failure cross-section is still influenced by the homogeneity of the preceding MCCI, it will quickly widen during the outflow of the accumulated 400 t of hot melt. The predicted melt discharge rates are in the order of 1 t/s and above.

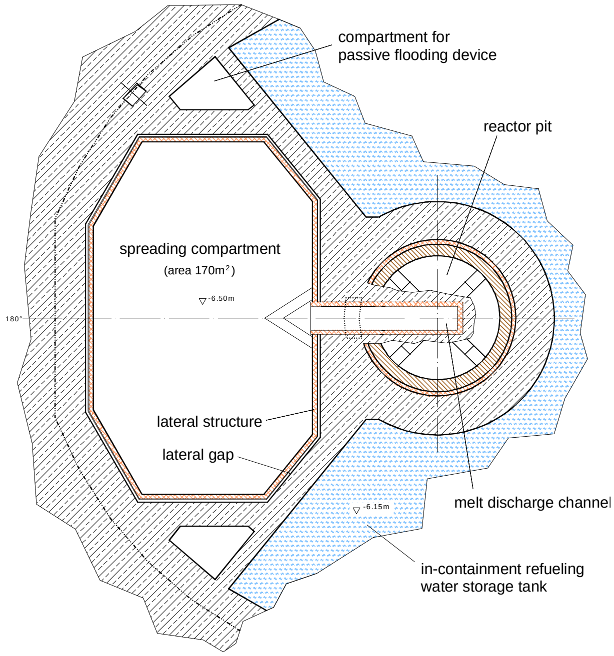

Fig. 3: Horizontal section through the lower part of the EPR containment showing the transfer channel between pit and spreading area, the IRWST and the compartments for the flooding valves

After passing the gate, the melt flows along the transfer channel and finally pours into the core catcher which forms the bottom of the spreading compartment, see Fig. 2. The inflow level is at an elevation that exceeds the maximum level the melt can reach in the core catcher.

Corium spreading has been extensively investigated in a number of experimental programs. The obtained data and findings resulted in the development of validated analytical tools, which predict that, already for small outflow cross-sections of < 0.1 m², the corium will spread quickly and evenly on the provided area. This is confirmed by tests with prototypic corium /4/, which yielded spreading lengths in the order of 10 m - the size of the EPR core catcher - already at melt discharge rates of < 100 kg/s.

As the spreading compartment is a dead-end room that is isolated from the rest of the containment there will be no inflow of water from sprays, leaks, or other kind of spillage prior to the arrival of the melt. As a consequence, spreading will take place under dry conditions. Though such conditions are not required for a successful spreading, they make the distribution process more predictable, as they eliminate the potential of local FCI's.

MELT FLOODING, QUENCHING AND COOLING

The EPR core catcher acts as a large, shallow outside-cooled crucible. Its bottom and sidewalls are assembled from cast iron elements, connected among each other by a slot and feather technique, see Fig. 3. The achieved structural flexibility avoids problems resulting from thermal deformation after heat-up. The inner surface of the core catcher is covered with sacrificial concrete, which protects the cooling elements from transient thermal loads during spreading. Water leak-tightness of the connections between the elements is not required, as concrete wetting from below is acceptable, or even advantageous.

Melt arrival in the core catcher will result in the opening of the two redundant spring-loaded flooding valves. Their initiation is triggered by the thermal destruction of pre-stressed signal wires. The valves allow gravity-driven overflow of water from the IRWST. The water first fills the central supply duct underneath the core-catcher, which connects the triangular valve compartments, see Fig. 2. From there the water enters parallel, slightly tilted channels, formed by the fins at the bottom of the cooling elements, see Fig. 3 and Fig. 5 that connect the central channel with the sidewall structures on the east and west side of Fig. 2 and then submerges the vertical space behind the structure. With the chosen initial flooding rate of 100 kg/s, the fill-up process takes about 5 min.

The following overflow results in a flooding of the melt from the top. Water flow continues, at about the same rate, until the water level atop the melt reaches the top of the sidewall structure.

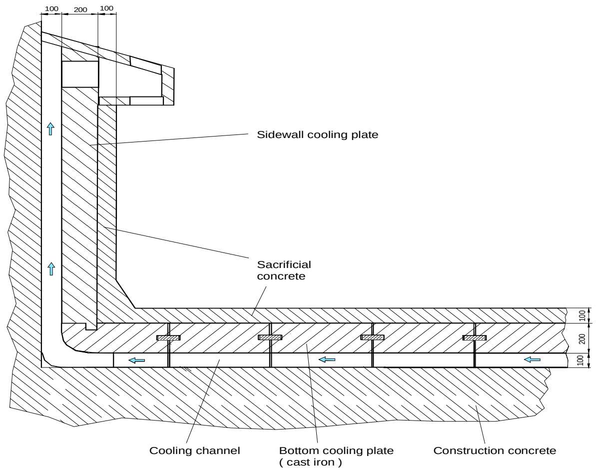

Fig. 4 Section through the horizontal and vertical part of the EPR core catcher (measures are indicative)

Once the water level atop the melt has reached the overflow level, the water inflow rate starts to decrease until finally, the hydrostatic pressure levels within spreading room and IRWST are balanced. In quasi steady state the inflow matches the rate of evaporation, and thus the level of decay power in the melt. In parallel with the flooding process, the melt interacts with the sacrificial concrete layer. For the actual concrete thickness of 10 cm, the MCCI is predicted to last about 20 min. When the cooling structure is reached, the collapsed melt height will be about 40 cm. At that time the predicted density difference between the heavier metallic and the lighter oxidic fraction is about 2 t/m³.

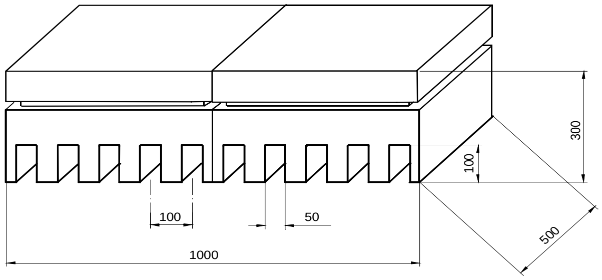

Fig. 5 Elements of the EPR core catcher with integrated cooling channels (measures are indicative)

For the lighter oxidic melt flooding under MCCI conditions is expected to lead to the quick formation of an oxidic crust, due to the low level of decay power per unit area. At the same time, the superheated metallic melt at the bottom will cause high erosion and gas rates. As this constellation favors melt ejections into the water and crust break-up, about 20 wt% of the oxidic melt fraction are predicted to become coolable as a result of fragmentation processes at the top. However, this value is not credited for demonstrating the function of the core catcher. Melt stabilization can exclusively be achieved by thermal conduction through the forming top and bottom crusts.

The highest heat fluxes into the cooling structure occur during the initial contact. Analysis shows that the combined effects of: (i) the temperature reduction by sacrificial concrete addition during the preceding MCCI and (ii) the thermal inertia of the massive cooling elements, ensure that the resulting transient heat fluxes into the water remain sufficiently low. Estimated peak values are about 80 kW/m² and 160 kW/m², respectively, at the bottom and the sidewalls (both related to the inner surface). Steady-state heat fluxes into the water (typically reached after 2-6 h) are significantly lower than these peak values.

Downward heat fluxes were found to be widely insensitive against the distribution and height of the metallic and oxidic melt fractions. This is due to the fact that the down/up-ratio of the heat transport decreases in deeper pools. Thus even highly unfavorable configurations, including postulated local accumulations, will be tolerated.

For the CHF-limit in the vertical part of the cooling channel (behind the sidewalls) the available data from the literature show comfortable margins.

For the less well-known horizontal part dedicated experiments were performed by FANP in a full-scale 5 m long channel [5]. They confirm that the maximum capacity of the existing structure, even in steady-state, is at least 120 kW/m². Up to this value, the channel showed a good-natured behavior under both, co- and counter-current flow conditions of the water and steam. Higher heat fluxes could not be tested as they would have exceeded the operational conditions of the heating system used for the experimental setup.

As a consequence of the observed independence, there is no need to ensure certain water inflow conditions for the individual channels. Instead, it is sufficient to keep the structure submerged, which is achieved by the connection with and the permanent overflow of water from the IRWST.

The excellent performance of the cooling elements stems from the use of vertical fins, see Fig. 5. They allow heat transfer to the water through both, the horizontal and vertical surface of the created channels. Therefore the formation of an insulating steam layer in the upper part of the channel does not result in a local dry-out.

Due to the high surface-to-volume ratio after spreading and to the fact that the melt is completely surrounded by cooled surfaces, a safe enclosure of the corium within stable crusts is achieved soon after the end of the MCCI.

The performed analysis shows (Fig. 6) that the denser metallic melt fraction at the bottom will freeze within the a few hours. The complete solidification of the decay heat-generating oxidic melt will typically take several days.

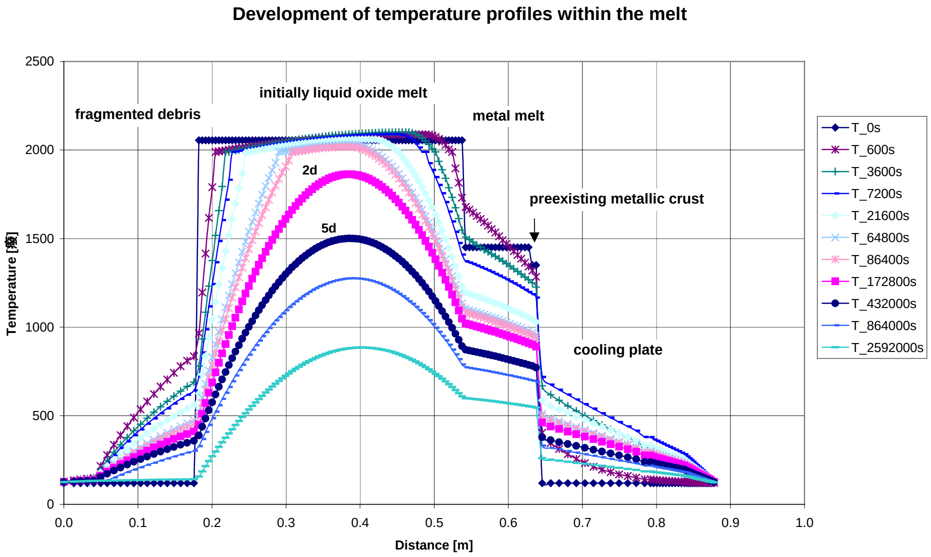

Fig. 6: Temperature profiles within the melt and the core catcher structure

LONG TERM HEAT REMOVAL FROM THE CONTAINMENT

The EPR uses a dedicated containment heat removal system with external heat exchanger and pumps. The Containment Heat Removal System (CHRS) takes suction from the IRWST, and re-injects the cooled water into the containment. The external recirculation loops are located in separate, ventilated and shielded compartments with provisions for decontamination and repair. The internal containment structures provide sufficient heat capacity, so that the design pressure is never exceeded earlier than 12 hours after scram, which defines the grace period for the availability of the CHRS. As schematically shown in Fig. 6, the CHRS has two trains and two principle modes of operation.

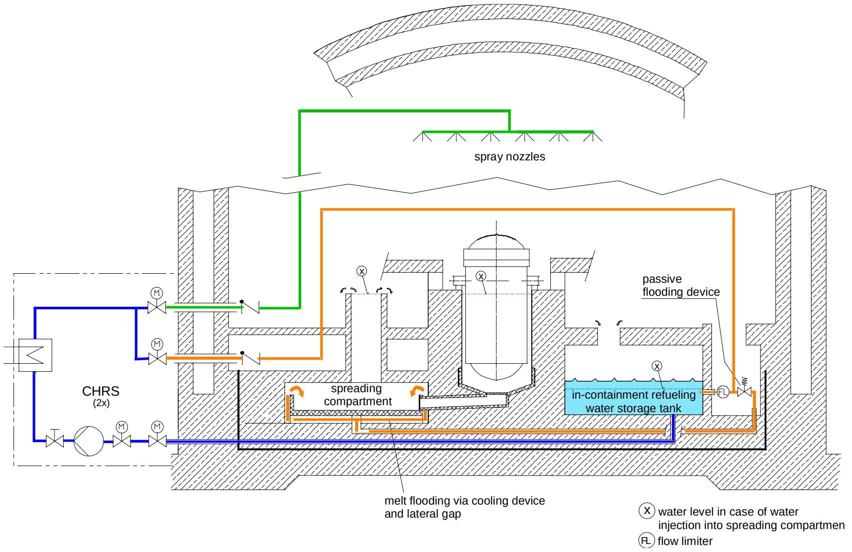

Fig. 7 Schematic of the CHRS, illustrating the two modes of operation (by spraying and/or direct feed into the core catcher)

In the first mode, the cold recirculated water is sprayed into the containment atmosphere to reduce the containment pressure and to washout air-born fission products. During this period the cooling of the core catcher is fully passive and the water levels are, as indicated in Fig. 8.

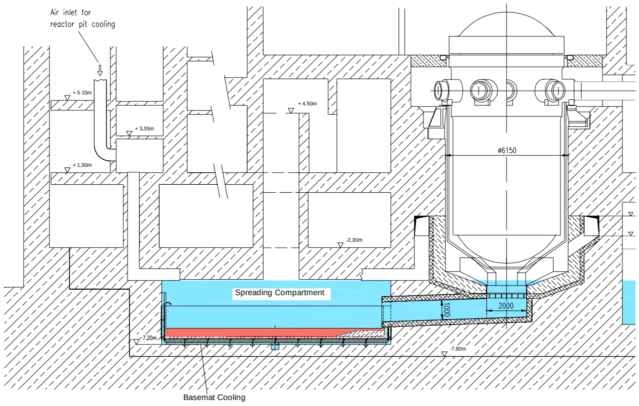

Fig. 8: Water levels within IRWST, spreading compartment and pit during spraying (passive melt cooling)

In the second mode, one or both trains of the CHRS can be used to feed water directly into to the core catcher. As a result, the water in the cooling channels and atop the melt will become sub-cooled. Decay heat can now be removed by single-phase flow, instead by the evaporation of steam into the containment atmosphere.

This allows to reach an ambient pressure level in the containment and thus to terminate the further release of activity through potential leaks.

Ambient pressure conditions can be achieved because only very limited amounts of non-condensable gases are generated during the preceding MCCI in the pit and spreading compartment. Further, among the released gases, hydrogen will be recombined to steam, which condenses at the walls and therefore does not contribute to containment pressurization.

In the active mode of CHRS operation, the water level in the spreading room will rise to the top of the steam outlet chimney, see Fig. 9.

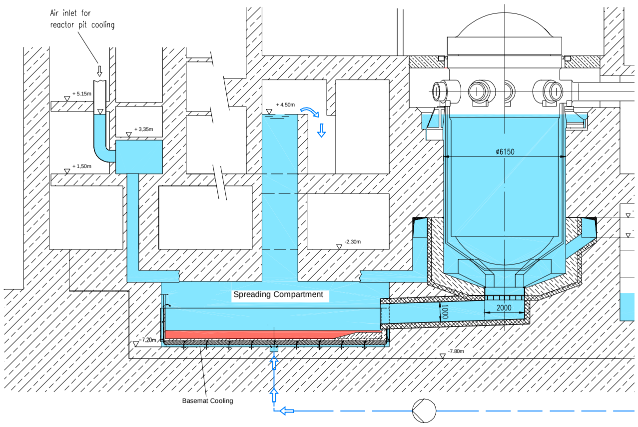

Fig. 8 Water levels within IRWST, spreading compartment and pit during direct feed into the core catcher (active melt cooling)

From there, the water overflows onto the heavy floor and drains back into the IRWST, thus closing the loop for the CHRS. As the spreading room and the reactor pit are connected via the transfer channel and the open gate, water will also enter the reactor pit and submerge the RPV up to the level of the loop-lines. This establishes long-term cooling for any debris that potentially remained either in the transfer channel, the pit, or the RPV itself.

The combination of melt stabilization, which terminates the MCCI, and containment heat removal, which avoids further steam release) eliminates the need for a containment venting system. This further decreases the release of radioactivity into the environment after a severe accident.

VALIDATION

The EPR melt retention concept has been developed under the premise to keep the necessary R&D effort low, by avoiding phenomena and situation with a high inherent uncertainty. If necessary dedicated design changes were implemented to achieve this target and to influence processes towards higher predictability. Examples are:

(i) the functional separation between the pit and core catcher. It allows to design the pit in a robust way, so that it can absorb the potentially high loads during RPV-failure, while - at the same time - the core catcher can be optimized for its cooling function.

(ii) the implementation of the phase of temporary melt retention and accumulation in the pit. It equalizes the melt properties, incl. mass and temperature, and thereby makes subsequent retention measures predictable and independent of the preceding accident.

Regarding the phenomena that govern MCCI, melt-material interaction, melt spreading and melt coolability, the validation relies on the knowledge elaborated within national and international R&D projects. On the issues of melt gate failure and heat transfer within the cooling channels, dedicated, supplementary investigations were performed by national partners and FANP itself. The analysis performed on the basis of the obtained knowledge base demonstrates considerable margins in all phases of the concept. Therefore no further R&D is necessary.

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