MITIGATION OF SEVERE ACCIDENTS IN AREVA NP'S GEN 3+ NUCLEAR POWER PLANTS

M. Fischer, A. Henning, R. Surmann
AREVA NP, E&P Division, Erlangen, GERMANY-91054
E-mail of corresponding author: manfred.fischer@areva.com

ABSTRACT

To ensure a safe operation all current AREVA Gen3+ PWR designs rely on proven and improved defense-in-depth safety concepts inherited from their predecessors, the French "N4" and the German "Konvoi" reactors. Complemented by specific enhancements, including higher redundancy and diversity, as well as the use of passive systems this leads to very low values of the core damage frequency (CDF). Notwithstanding this very low probability, specific severe accident (SA) design measures are implemented aimed at keeping the large-early-release-frequency (LERF) and the environmental radiological consequences of a postulated SA with core-melting low, by preserving the containment integrity throughout the course of the SA. Short-term situations that potentially lead to high loads on the containment, like RPV melt-through under high pressure, energetic hydrogen / steam explosions, and long-term containment failure by internal over-pressure are avoided by preventive measures and dedicated systems, including for the stabilizing the molten core.

At the example of the EPR™, the paper gives an overview of the severe accident mitigation strategy and the related measures and systems of AREVA NPs Gen3+ PWRs.

INTRODUCTION

All of AREVA NPs advanced Gen-3+ reactor designs, the EPR™, and ATMEA1™ PWRs as well as the KERENA™ BWR give extended consideration to the prevention of severe accidents. Despite the achieved very low values of the core melt frequency additional measures, capable of drastically reducing the environmental impact in case a severe accident (SA), are implemented in the design. Their target is to eliminate the need for emergency evacuations of the surrounding population and for long-term restrictions with respect to the consumption of locally grown food even in case of such highly unlikely event. The adopted safety concepts meet advanced regulatory requirements, including IAEA safety guide, Technical Guidelines (GPR/German experts), and SECY 93-087 (NRC).

The SA mitigation concept is illustrated at the example of the EPR™ PWR, a 4-loop reactor with a power of about 4650 MWth, currently under construction in Finland, France and the P.R. China.

EPR™ SEVERE ACCIDENT MITIGATION STRATEGY OVERVIEW

A severe accident commences when loss of emergency core cooling functions have failed to maintain the core in a coolable geometry and, importantly, the core fails to remain in a stable configuration. In order to achieve the international consequence targets, the EPR™ is equipped with dedicated severe accident mitigation measures that are 'novel' to existing PWRs, see Fig. 1. These measures aim at preserving the containment integrity not only during a limited time but throughout the SA. To achieve this target a balanced approach adequately considering all related challenges and containment failure modes is followed.

Short-term situations potentially leading to high thermal and mechanical loads on the containment, like RPV high pressure melt-through or energetic hydrogen and steam explosion are excluded by adequate preventive measures. For the resulting low pressure sequences, mid- and long-term containment failure, caused by over-pressurization or basemat melt-through, is avoided by a combination of design measures and dedicated systems.

For the proof of function of these systems a wide spectrum of initiating events and scenarios, including Large Break (LB)-LOCA, Small Break (SB)-LOCA, Loss of Offsite Power (LOOP), and Total Loss of Feed Water (TLOFW) and a successful depressurization of the primary circuit are considered. The related demonstration is provided on a deterministic basis, applying best-estimate assumptions and methods. During the SA, dedicated instrumentation allows monitoring the course of events and deviation from the predefined mitigation path.

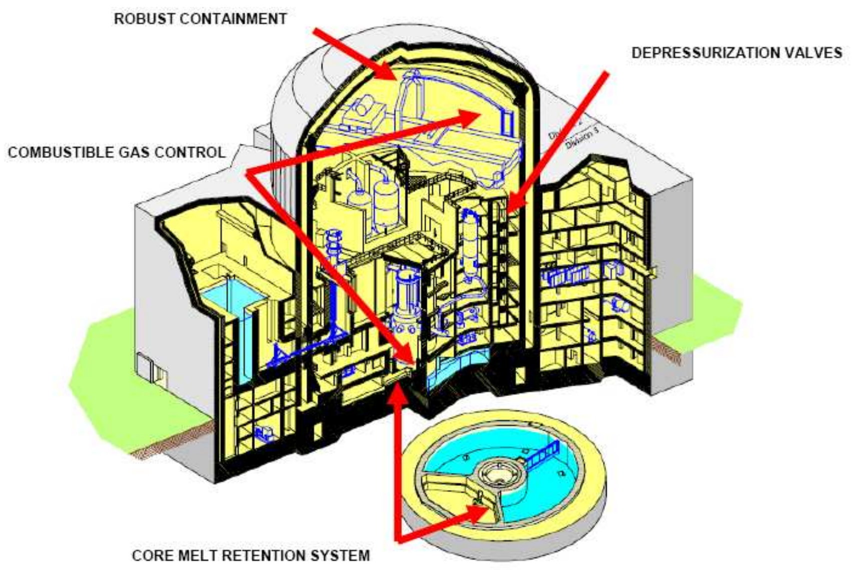

Fig. 1: EPR™ Plant Scheme, with Severe Accident Mitigation Measures

In addition, the robustness of the SA mitigation systems and their ability to preserve containment leak-tightness is demonstrated also under bounding, beyond-design conditions including elevated RPV failure pressure or internal late reflood. As compared to these, the postulated complete failure to depressurize the primary system is considered as residual risk and only evaluated in PSA level-2.

PREVENTION OF HIGH PRESSURE RPV FAILURE

Melt-through of the RPV under high system pressure involves the risks of energetic missiles and High Pressure Melt Ejections (HPME) leading to Direct Containment Heating (DCH). Because of the related risk of short-term containment failure the reliable transfer of high pressure into low pressure core melt sequences is of paramount importance for preserving the containment integrity in case of SA. To ensure this depressurization, the EPR™ provides two redundant lines, each with two dedicated high-capacity SA (PDS) valves in series, in addition to the existing three pressurizer safety valves (PSV), see Fig. 2. The PDS valves are manually activated, at the latest when the core outlet temperature exceeds 650°C. The sizing of the PDS valves ensures rapid reduction of the primary system pressure below 5 bar. Any later pressure increase is only possible as a consequence of reflood.

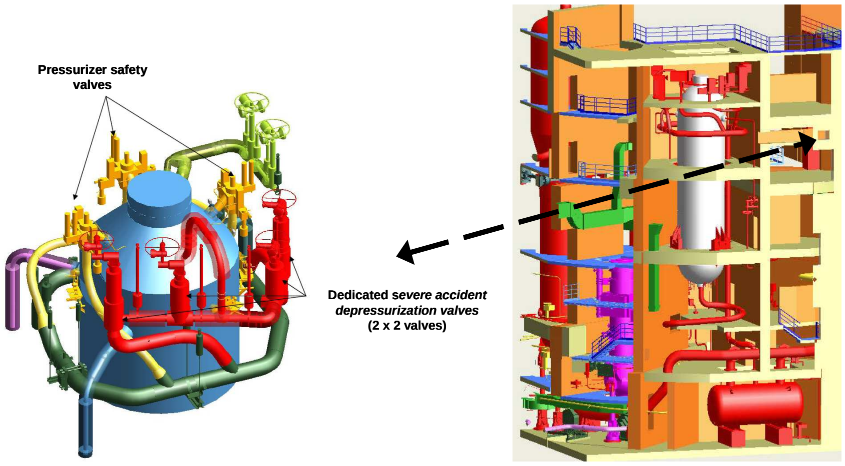

Fig. 2: EPR™, Positions of PSV/PDS valves and PRT tank relative to the pressurizer

High redundancy for opening the valves is achieved by associating their electrical and I&C systems to all 4 plant divisions. The required power to open can be alternatively provided by Off- and On-site Electrical Systems, including SBO diesels, as well as by two long-duration (>12h) dedicated SA batteries. The PDS and PSV valves feed into a 40 m³ pressure relief tank (PRT), which – after failure of a 20 bar rupture disc - discharges into two out of the four reactor coolant pump (RCP) rooms. Direct release into the containment was preferred against condensation in the IRWST because of combustible gas mixing and steam inertization.

PREVENTION OF ENERGETIC STEAM EXPLOSIONS

A steam explosion can evolve from situations with an intense interaction between molten fuel and water and heat transfer through stable film boiling. Any pressure wave passing through the water can then disrupt the vapor film causing direct contact between the hot surface and the water which may synchronously triggers a rapid exchange of energy amplifying the primary wave. Given a sufficiently long interaction period this process can continue until a shock wave is formed. Preconditions are a subcooled water pool and the absence of non-condensable gases.

If conditions are favorable, a steam explosion may happen at different stages in the progression of a severe accident, most notably, when melt drains from the core into the residual water in the reactor lower head and following vessel failure, should the melt relocate into a region containing water.

In-vessel steam explosion

No specific countermeasures against in-vessel steam explosions are taken in the EPR™ design. This is because the probability of an in-vessel steam explosion, sufficiently energetic to damage the RPV upper or lower head, can be shown to be very low. This demonstration is based on best-estimate views on melt progression/relocation and conversion efficiencies and supported by modeling and experimental databases. The obtained results are consistent with the view of the OECD SERENA-1 project, which concludes that this mode of vessel failure can be considered as resolved from a risk perspective, meaning that it is of very low likelihood and of little or no significance to the overall risk from a nuclear power plant

Ex-vessel steam explosion

The EPR™ SA mitigation strategy does not involve retaining the molten core inside the vessel. Instead a dry reactor pit is provided. Also the ex-vessel core catcher is initially dry as it is located in an isolated compartment. Unintended leakage from the IRWST can be detected and terminated. These measures eliminate the risk of energetic ex-vessel steam explosions resulting from melt entering into a water pool.

The final flooding of the spread melt in the core catcher is performed at low flow rate, and during reaction with sacrificial concrete. Due to the related intense superficial agitation of the melt pool, all added water will initially evaporate. Consequently, a deep water pool can only form after the melt's surface is no longer liquid but covered by a solid crust. There is a large experimental data base demonstrating the absence of steam explosions in corresponding situations of top flooding during molten core concrete interaction (MCCI).

PREVENTION OF BASEMAT MELT-THROUGH

In-Vessel- vs. Ex-Vessel Melt Retention

In-vessel retention (IVR) attempts to stabilize the molten core within the RPV by sustained cooling of the outside of the vessel. This solution is attractive as it minimizes the dispersal of melt and requires only limited additional hardware. The success of IVR is related to the question: does the heat flux to the water – at any time - stay below the local "Critical Heat Flux" (CHF)? A "departure from nucleate boiling" with transition to film boiling can lead to a fast increase in the local RPV wall temperature (by up to a thousand degrees) potentially followed by creep failure or melt-through, if this area becomes large enough.

The answer lies in the thermal analysis of the combined system of melt, RPV wall, internal structures, and external 2-phase flow. The heat flux at the outer surface of the RPV depends on the natural convection pattern inside the molten pool and on the formation and spatial distribution of stratified metallic and oxidic melt layers. The fact that sideward heat transport by convection/conduction out of a molten metallic (steel) layer is more efficient than radiant heat transport off its free surface, gives rise to what is known as the "focusing effect". A low-density metallic phase located atop the decay heated oxide can thus concentrate most of the thermal power it receives from the oxide pool below to its circumferential contact region with the vessel. For thin molten metal layers, the "focused" heat flux can be very high and by far exceed the maximum heat flux in the oxidic pool below.

This is, in particular, true for small-sized vessels and reactors with high thermal (and decay) power. The evolution of the thickness of the upper metallic layer is not only defined by the melting sequence of the steel internals but does also depend on thermo-chemical processes that can create dense U-rich metallic phases suspended at the bottom of the oxidic pool [1]. This leads to high uncertainties in predicting the thickness of the upper metal layer and the thermal loads on the vessel. Considering also that:

- low margins for IVR involve the risk of steam explosion-induced early containment failure after vessel melt-through
- due to the open (via initiating leak and/or open PDS-valve) primary circuit and the long-lasting very high pool temperatures, the activity release into the containment is high also in case of IVR

it was decided to sacrifice RPV integrity for the EPR™ and ATMEA1™ in favor of controlled melt stabilization in an ex-vessel core catcher. Instead, for the KERENA™ BWR, due to the large size of its vessel, the long grace period before core melting, and the large internal steel masses, IVR is used [2].

Core Melt Stabilization Strategy Overview

Core melt stabilization by a dedicated system, the CMSS, see Fig. 1. It prevents interaction between the molten core and the basemat and thus eliminates the risk of containment failure due to:

- the penetration by the embedded containment liner
- the long-term heat-up and mechanical deformation of the containment civil structure
- the sustained release of non-condensable gas into the containment

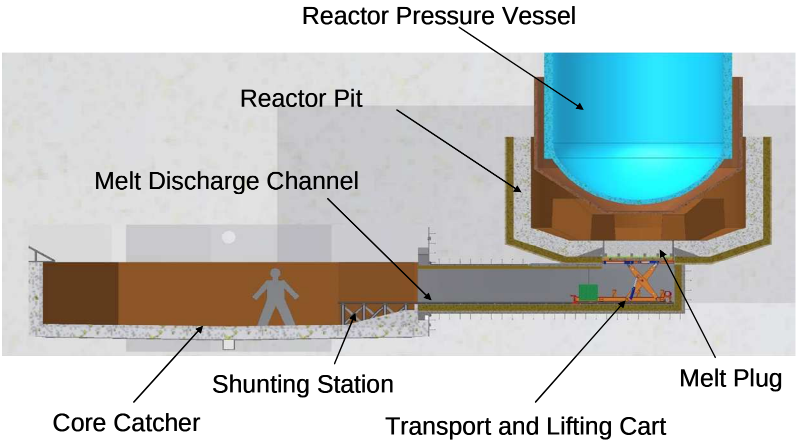

Fig. 3: EPR™ Core Melt Stabilization System, Main Components

The main component of the CMSS is the so-called core catcher (CC), a large metallic crucible into which the melt spreads and where it is quenched and cooled. The CC is located in a dedicated compartment lateral to the reactor pit, see. Fig. 3. By its spatial and functional separation from the pit the core catcher is decoupled from the loads related with the initial RPV failure, which are absorbed by the structures located in the reactor pit. In addition, safety risks linked with a postulated unintended flooding of the core catcher during power operation also eliminated.

Gravity-driven melt relocation into the core catcher is preceded by a phase of temporary melt retention in the reactor pit during which the already released melt fraction interacts with sacrificial concrete (at bottom and sides) and at the same time with the residual lower head (above). This ensures incorporation of all core material into the molten pool long before the time when the concrete melt plug in the centre of the pit bottom is penetrated.

The melt then flows into the core catcher via an embedded melt discharge channel and activates the opening of passive flooding valves that start the overflow of water from the Internal Refueling Water Storage Tank (IRWST). After filling the space around the CC, the coolant eventually pours onto the surface of the spread melt. At the end of the quench period the melt is completely surrounded by water or water-cooled metallic structures and all decay heat produced inside the melt is extracted by heat-up and evaporation of the coolant water.

Along the described sequence, the transformation of the molten core into a coolable and permanently cooled configuration is achieved passively, on the basis of simple physics and without requiring operator action or the use of internal or external active systems.

Controlled state approach

No exact prediction on how the core will degrade, melt and penetrate the vessel, in a certain severe accident scenario is possible, since the course of in-vessel events depends on:

- the state and history of the core (bundle characteristics, burn-up, etc.)
- the details of the preceding accident scenario (initiating event, operator response, etc.)
- stochastic processes during core degradation/melting (like material relocation, crust break-up, etc.)

In addition, there exist large uncertainties in the prediction of the underlying thermal, mechanical and chemical processes, in particular during the late phase before vessel failure.

This inherent uncertainty was considered already at the design stage of the EPR™ SA mitigation concept by introducing measures in the reactor pit that influence the course of events into the direction of a higher predictability. This makes the following mitigation path independent of the preceding conditions at vessel failure and eliminates the necessity to analyze and predict these conditions in detail.

By applying this approach, which is described in detail in the following paragraph, intermediate melt states and conditions at the time of melt plug failure are generated which are sufficiently defined and for which sufficiently assured knowledge exists. As a consequence only a narrow spectrum of conditions needs to be considered for the proof of the subsequent CMSS functions: (i) melt spreading, and (ii) short- and long-term core catcher integrity.

Melt Accumulation and Conditioning for Spreading

In case of SA, the release of the molten material from the RPV will, most likely, not take place in one pour but during a certain period of time. To ensure that the entire core inventory relocates into the core catcher in one predictable event, a phase of temporary melt retention and accumulation in the pit was introduced. It is based on the provision of a layer of sacrificial material that must be penetrated by the melt prior to its escape from the pit.

The sacrificial concrete layer is completely surrounded by a melt-resistant ceramic layer, which protecting protects the civil structure and thus compensates inhomogenities in the concrete erosion process. The protective layer has only one penetration, at the position of the removable melt plug in the center of the pit bottom. The melt plug therefore acts as the predefined release location for the melt. It is shielded against mechanical impact of the lower head by concrete bumpers arranged around it.

Starting with the initial RPV melt-through, the released part of the melt interacts with the sacrificial concrete. During MCCI the heat flux emitted from the surface of the pool heats the RPV lower head from below. In addition, there is direct contact after about half of the core material is released. Heating from below is supplemented by the decay heat generated in-vessel. Considering that:

- downward heat transport in the MCCI pool is, at the best, as effective as upward/sideward heat transport
- the total sideward heat transport is limited by the amount of concrete provided in front of the protective layer (which, after exposure, acts as an insulator)
- most of the heat transported upward enters the RPV lower head

it can be shown that: (i) the progression of the MCCI in downward direction is linked with the heat-up of the RPV lower head, and (ii) the amount of heat carried into the lower head is mainly determined by the thickness of the eroded sacrificial concrete and therefore widely independent of the decay power level (scenario) and the sequence of melt release from the RPV.

Whenever the lower head has absorbed a sufficient integral amount of heat, it is considered to collapse into the MCCI pool, carrying with it the remaining in-vessel fraction of the core. Corresponding analysis shows that, even under conservative assumptions, this will happen before half of the provided concrete layer is ablated.

In the further course of the MCCI practically all provided sacrificial concrete is incorporated into the MCCI pool. The resulting, rather well-defined concrete fraction makes the state and properties of the melt at the end of the accumulation period predictable.

The total duration of the retention period depends on the decay power level and is typically between one and three hours. The end is defined by the thermal destruction of the “gate” consisting of aluminium which forms the bottom of the melt plug. The out-flowing melt enlarges the initial hole which progressively accelerates further melt release. A sufficiently fluent state of the melt at this time is ensured by the fact that, during the preceding MCCI, the pool had to remain convective to carry the decay power to the surrounding cold interfaces.

The out flowing melt is guided through a discharge channel into the core catcher, see Fig. 3. The channel surface is also covered with a protective layer which can withstand the related mechanical and thermal loads. As the channels exit level is above the maximum melt level in the core catcher, practically all melt will be discharged.

Melt stabilization in the core catcher

The EPR™ core catcher, see Fig. 4, is a massive cast iron structure weighing about 500 tons and being assembled from a large number of individual elements that are connected with each other using a tongue and groove technique. The achieved structural flexibility avoids problems resulting from thermal deformation and non-homogeneous heat-up by the melt. The joints between the elements are closed by steel elements and compressible, temperature-resistant mineral wool. The inner surface of the structure is covered with concrete to protect the cooling elements from transient thermal loads during melt spreading.

The arrival of the melt triggers the opening of redundant passive valves located in compartments lateral to the core catcher which, after being destroyed by the arriving melt, initiate the gravity-driven overflow of water from the IRWST. Both melt arrival in the core catcher and the successful opening of the valves can be detected by SA-qualified instrumentation. The incoming water passes a central supply duct underneath the core-catcher and then rises into a system of parallel cooling channels formed by the fins of the bottom and sidewall cooling elements, see Fig. 4. Next, the water submerges the space behind the sidewall structure and finally pours onto the surface of the melt from the circumference. The outside of the cooling structure is completely submerged before any significant heat-up by the melt. This is due to the thermal insulation provided by the sacrificial concrete during MCCI and the high thermal inertia of the cooling elements.

As long as the IRWST contains water the spread melt is kept submerged and cooled via passive overflow. During this period the created steam enters the containment via a vertical chimney, leading above heavy floor level.

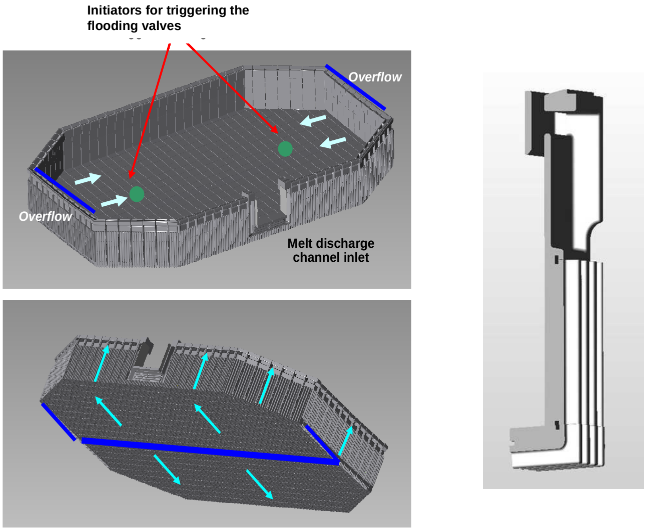

Fig. 4: EPR™ Core Catcher Structure (left) and Individual Lateral Cooling Element (right)

The efficiency of the core catcher is demonstrated based on analyses and experiments performed in an electrically heated 1:1 mockup of the cooling channel. The high thickness of the cooling structure results in a robust thermal behavior characterized by a low sensitivity against transient phenomena, including the initial melt contact.

The heat flux from the melt to the upper surface of the cooling plate is determined analytically, using conservative assumptions and measured data on heat transfer obtained from prototypic spreading experiments. The considered conservatism includes the assumption of zero superficial fragmentation, despite the fact that partial coolability can be expected in case of melt flooding under MCCI conditions.

The design and technical realization of the EPR™ CMSS is described in [3].

PREVENTION OF H2 COMBUSTIONS AND EXPLOSIONS

Combustible gases, namely hydrogen, impose a potential threat for the containment integrity because of: dynamic pressure loads resulting from energetic events (detonations), and quasi-static pressure and temperature loads resulting from slower burns, including standing flames. Detonations are of concern mainly during the early stage of the severe accident (in-vessel hydrogen production phase), when hydrogen concentrations are high and the steam partial pressure is still low.

To control the hydrogen content in the containment atmosphere in case of SA, the EPR™ is equipped with a dedicated Combustible Gas Control System (CGCS). It consists of two parts: (i) a passively activated and operating atmospheric mixing system which - early into the accident - transforms the former 2-room into a 1-room containment, and (ii) a large number of autocatalytic recombiners strategically placed in the containment and able to deplete hydrogen, even under steam-inert, severe accident conditions. The combined functional requirements are to:

- limit the concentration in the containment to <10 vol.%, in order to avoid a global detonation
- allow higher concentrations than 10 vol.% only temporarily and only in small regions

The success of these measures can be evaluated during SA using data delivered by the Containment Atmosphere Monitoring Systems (CAMS).

The transformation from the 2-room (DBC1&2) into a 1-room containment (DBC3&4 and DEC) takes place passively by (i) the fast opening of large free flow cross-sectional areas at the pressure equalization ceiling, and (ii) the opening of additional atmosphere inlet areas between annular rooms and equipment rooms near the IRWST level. As a consequence, convection flow is established throughout all relevant containment areas (equipment rooms, dome area, annular rooms, IRWST). Gas mixing is additionally supported by the low level of the PRT discharge lines, see Fig. 2, and the hot exhaust gas released from the autocatalytic recombiners, see Fig. 5.

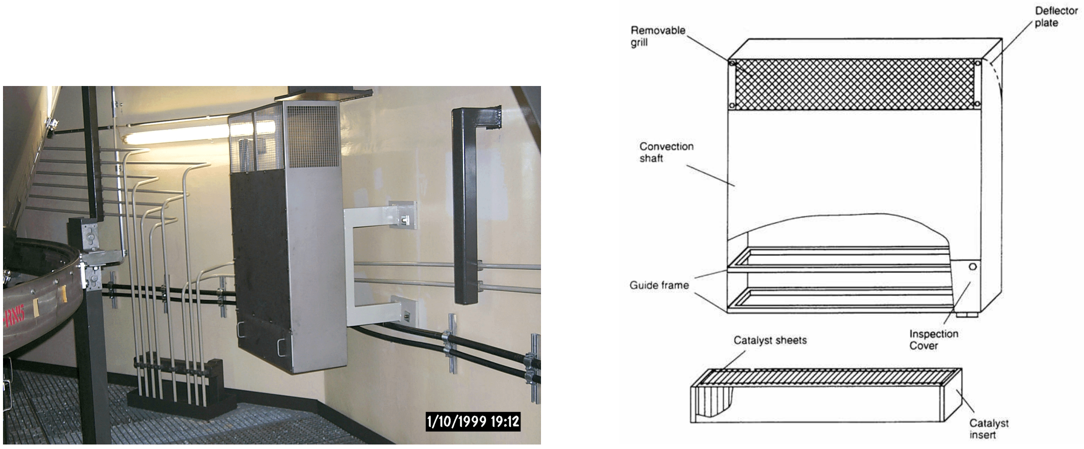

Fig. 5: AREVA NP Autocatalytic H2-Recombiners, when installed (left) and inner structure (right)

The number and total capacity of these recombinors are chosen to be able to decrease the global H2-concentration in the containment, for a released H2 mass corresponding to 100% cladding oxidation, below 4 vol% within a few hours. In combination, short-term global hydrogen concentration in the containment must stay below 10 vol%. In the long-term, practically all hydrogen is removed from the containment atmosphere, which eliminates the possibility of further hydrogen combustions. An overview of the function of the EPR™ CGCS and the applied validation strategy is given in [4].

PREVENTION OF CONTAINMENT OVERPRESSURE FAILURE

For containment p&T control, the EPR™ is provided with a dedicated Containment Heat Removal System (CHRS) which is specifically qualified for SA conditions. Due to the large free volume of the EPR™ containment and the high heat storage capacity of its internal structures, activation of the CHRS is not required for keeping the containment pressure below the design pressure during a 24h grace time.

The CHRS takes suction from the IRWST through dedicated screens and re-injects the cooled-down water into the containment either via the spray system (which cools the atmosphere and condenses steam) or via the core melt spreading compartment. All compartments housing components of the CHRS outside the containment are specifically protected and isolated and can thus be considered as an extension of the containment. The CHRS consists of two trains and uses a separate cooling chain.

During the first days, the main target is to reduce the containment pressure and to wash-out air-born fission products. During this period, spraying is the preferred CHRS mode. Later, one or both trains can be used to feed water directly into the spreading compartment. This lifts the water level above the overflow level to the heavy floor. From there the water flows back into the IRWST, thus closing the loop for the CHRS.

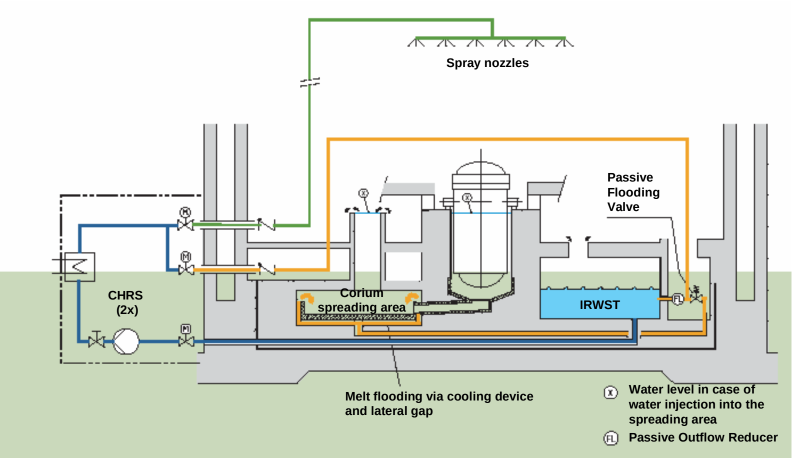

Fig. 6: CHRS flow scheme for spraying and direct injection into the core catcher

In this mode, the decay heat is removed by single-phase water flow instead of by evaporation and steam release into the containment. Ambient pressure can thus be reached without the need for venting. Further, as the spreading room and the reactor pit are connected through 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 potentially remaining in the RPV, the pit, and the transfer channel.

CONCLUSION

The EPR™ design involves a complete and balanced set of components and systems for severe accident mitigation. They operate on physical principles that are simple and sufficiently well understood. The potential impact of the remaining uncertainties is eliminated by a robust design of the components. The applied materials and components are commonly known and also used in other industrial applications.

The function of the SA systems is demonstrated for a wide spectrum of scenarios, based on analytical and experimental data and considering the state-of-the-art with respect to severe accident codes and the evolution of the core melt accident, incl. state and properties of the molten corium and its interaction with structural material.

The adequacy of the approach is reflected in the positive evaluation of the EPR™ SA concept in the EPR™ licensing procedures in Finland, France, China, the U.K., and the U.S.A. The ATMEA1™ design takes benefit of these achievements by adopting successfully validated solutions.

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