

## **Core melt stabilization concepts for existing and future LWRs and associated R&D needs**

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### **ABSTRACT**

In the event of a severe accident with core melting in a NPP the stabilization of the molten corium is an important mitigation issue, as it can avoid late containment failure caused by basemat penetration, overpressure, or severe damage of internal structures. The related failure modes may result in significant long-term radiological consequences and high related costs.

Because of this, the licensing framework of several countries now includes the request to implement mitigative core melt stabilization measures. This does not only apply to new builds but also to existing LWR plants.

The paper gives an overview of the ex-vessel core melt stabilization strategies developed during the last decades. These strategies are based on a variety of physical principles like: melt fragmentation in a deep water pool or during molten core concrete interaction with top-flooding, water injection from the bottom (COMET concept), and retention in an outside-cooled crucible structure.

The provided overview covers the physical background and functional principles of these concepts, as well as their status of validation and, if applicable, the remaining open issues and R&D needs. For concepts based on melt retention inside a cooled crucible that reached sufficient maturity to be implemented in current Gen-III+ designs, like the VVER-1000/1200 and the EPR™, more detailed descriptions are provided, which include key aspects of the related technical realization.

The paper is compiled using contributions from the main developers of the individual concepts.

## KEYWORDS

Severe accident mitigation, LWR, core catcher

### 1. INTRODUCTION

Different from existing Generation II nuclear power plants (NPP), which generally did not address severe accidents in their licensing, Generation III(+) NPP designs have to take into account correspondingly more stringent requirements, in accordance with the Safety Standard requirements formulated by the International Atomic Energy Agency [1]:

*“Consideration shall be given to severe accidents, using a combination of engineering judgement and probabilistic methods...”*

*“The occurrence of accidents with severe environmental consequences should be made extremely unlikely by means of preventive and mitigatory measures.”*

These requirements were further detailed on national levels, as in the European Utility Requirements [2]:

*There should be “no need for stringent countermeasures during the initial 24 hours subsequent to the onset of accident conditions, i.e. the evacuation of people should be avoided except in the immediate vicinity of the plant”.*

*“Long-term relocation should not be necessary beyond approximately 2 km from the plant.”*

*“Restrictions of the trade of agricultural products, which are produced in the vicinity of the plant, shall be necessary only for the first agricultural period after the accident.”*

To fulfill these tighter safety targets it is mandatory to preserve the integrity of the plant’s containment during a time period much longer than the first 24 h after a postulated severe accident.

### 2. CHALLENGES TO THE CONTAINMENT INTEGRITY DURING A SEVERE ACCIDENT

Under the extreme conditions of a severe accident with core melting, the integrity of the containment can be challenged in various ways. Specific consideration needs to be given to events and situations that can lead to early containment failure, due to the corresponding potentially large release of radioactive substances to the environment. Besides containment isolation failure, short term containment failure can be caused by:

High pressure core melting: This class of events and the associated risks can be avoided by reliable primary cooling circuit depressurization valves that are qualified for severe accident conditions.

Hydrogen detonation: This risk class can be mitigated by hydrogen recombiners and/or igniters, potentially combined with design features to enhance atmospheric mixing, hydrogen dilution and inertization (e.g. by steam or nitrogen).

Steam explosions: The steam explosion risk can be prevented by avoiding the uncontrolled discharge of large amounts of melt into water.

After successful prevention of short-term containment failure, the integrity of the containment is still under the risk of long-term overpressure failure, possibly caused by the absence of effective means to extract the decay power from the containment or by basemat melt-through by corium released from the reactor pressure vessel (RPV). Although the immediate radiological consequences of these failure modes are less severe compared to early containment failure, the related sustained release of radioactive substances to the environment is not consistent with the long-term radiological targets listed above.

### 3. EX-VESSEL CORE MELT STABILIZATION OVERVIEW

The interaction of molten core debris with the concrete basemat can result in complex situations which are difficult to predict and to control. These situations include:

- the penetration of the containment liner and the building structure with long-term contamination of sub-soil and ground water,

- the uncontrolled spreading of molten core debris into various areas of the containment,
- the heat-up and mechanical deformation of the containment civil structure, resulting in the formation of cracks and leaks, and
- the sustained release of hot gases, including steam and non-condensables (H<sub>2</sub>, CO<sub>2</sub> and CO) into the containment, leading to pressure and temperature build-up and the need for venting.

In addition, the successful stabilization of the molten will result in easier recovery operations in the long-term, as compared to the situation of an undefined distribution of the debris in the basemat concrete. Therefore, core melt stabilization is seen as an indispensable part of severe accident mitigation. For stabilizing the melt outside the RPV, various basic approaches exist, which are subject of this paper. The requirements on the function of ex-vessel core melt stabilization systems (CMSS) depend on the specifics of the plant and the applicable licensing framework. However, there exist generic features, which any CMSS must fulfill:

*Provide the capability to stabilize the core melt within the containment boundary*

*This encompasses the removal of the residual heat generated within the core debris usually by the heat-up and evaporation of water which preferably should come from reservoirs inside the containment. All involved components (including their actuation) should (as much as possible and practical) be passive. In addition, these components should remain functional over a long period of time, which implies that active components should be located outside the containment to allow for repair.*

*Immobilize and retain the radioactive substances contained in the core debris*

*This involves the trapping of all low-volatile elements still contained in the melt so that they cannot be further dispersed in the containment or released into the environment (in case of leaks). As these elements involve isotopes with a long life time, their stabilization is an important issue.*

*Avoid negative impact on other systems*

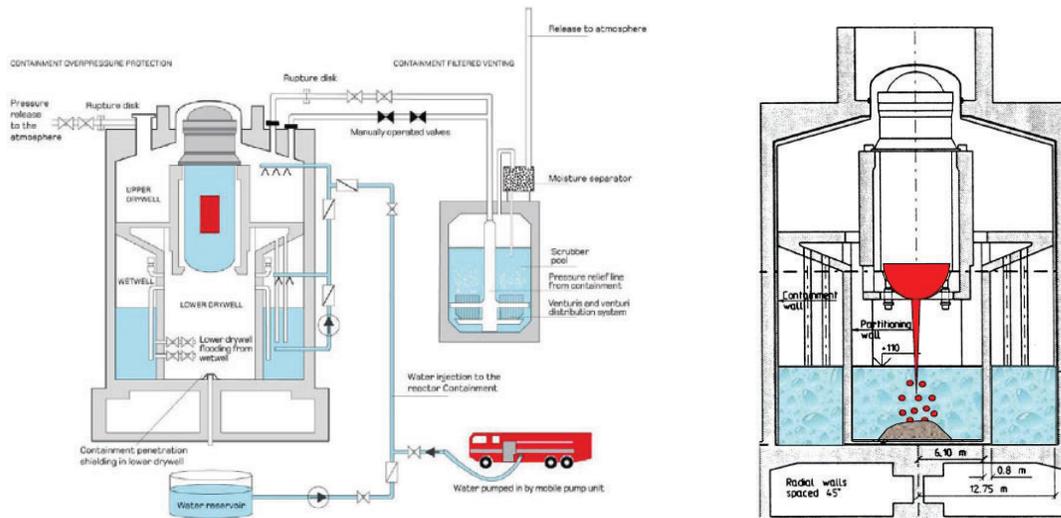
*The presence and operation of the CMSS must not negatively interfere with operation and service of the plant or with safety-related functions of other systems, before and during the severe accident.*

When implementing a CMSS into a Gen III(+) nuclear power plant a wide range of scenarios and initial conditions can be accomplished. When doing so for an existing plant, the covered range will be more narrow, because of various constraints and because severe accidents were not considered in the original design. The spectrum of CMSS concepts applicable for new and existing plants can be separated into two groups. Concepts of the first group, described in Chapters 4 to 5, require no changes to the existing containment and no dedicated components except for providing coolant water below the RPV in a severe accident. For transferring the core melt into a coolable state these concepts rely on certain fragmentation mechanisms. Any uncertainties in the efficiency of these mechanisms directly translate into more or less melt progression. As compared to this, the concepts of the second group, described in Chapters 6 to 9, establish a defined line-of-defense (the so called “core catcher”) inside the containment boundary. The individual concepts deviate among each other in the type of this boundary and the way it is kept intact.

## **4. MELT QUENCHING IN A DEEP WATER POOL**

### **4.1. Historical Background**

The strategy of melt quenching in a deep water pool was implemented in the Swedish BWRs in 1980s [3], based on a corresponding Swedish Government decision to minimize the radiological consequences of a severe accident for Swedish NPPs, which resulted in an extensive program of safety improvements [4]. The technical measures realized in Swedish BWRs as part of this program focus on containment protection and the elimination of early containment bypass, as illustrated in Figure 1-(a). Besides implementing filtered containment venting and an independent containment spray system, connectable to mobile equipment, the implemented measures also included a system for ex-vessel corium stabilization.



**Figure 1. (a) Overview of Severe Accident Mitigation Measures in Swedish BWR's [4] (left side). (b) Section of a BWR containment at the late phase of severe accident (right side)**

#### 4.2. Main Functional Principles

Severe accident mitigation strategy in Swedish and some Nordic BWRs includes comprehensive measures for corium melt ex-vessel retention, isolation and passive cooling. It foresees gravity driven flooding of lower drywell with water from the pressure suppression pool. Melt arrest and accident stabilization is provided by ex-vessel debris bed coolability. For this, a 7-12 m deep water pool is provided, Figure 1-(b), in which the core melt, after its release from the RPV, is expected to fragment, quench, and transform into a coolable particulate debris bed. Heat transfer from the corium particles is provided by water circulation through open pores in the debris bed. The implementation of the concept requires only minimum additional hardware, namely adequate means and water sources for the flooding of the cavity: Flooding must be complete prior to RPV failure to a final water level below that of the RPV bottom.

#### 4.3. Status of Validation

Swedish severe accident research to support the SAM for the BWR reactors was originally carried out in co-operation between SKI (now SSM) and the Swedish nuclear industry [3]. The technical basis for the implemented measures at all nuclear power plants in Sweden were supported by several research projects: like FILTRA, RAMA (Reactor Accident Mitigation Analysis), HAFOS and most recently in the framework of a series of the APRI projects (Accident Phenomena of Risk Importance). The major part of the Swedish research for corium retention is performed at the Royal Institute of Technology (KTH) in Stockholm at the Division of Nuclear Power Safety. Main results can be found in [5,6].

#### 4.4. Remaining Open Issues and R&D Needs

The main risks involved in the described SAM concept are: (i) the possibility of steam explosions during melt quenching, and (ii) the formation of a non-coolable debris bed at the bottom of the cavity, which can either lead to early or late containment failure.

For the steam explosion issue, answers are needed with respect to the probability and magnitude of the energetic interaction, as well as to the mechanical loads and the strength of the containment. Among the factors that determine the energy of the steam explosion the flow rate of the molten jet entering the water pool is considered of highest importance, as it determines the melt mass that is available for premixing, fine fragmentation and energy supply to the expanding pressure wave.

Therefore, the steam explosion phenomenon is strongly linked with the in-vessel melt progression, the mode of vessel failure and the melt release scenario. The debris bed coolability is affected by the mechanisms that drive jet fragmentation in water, particle quenching, settling, and spreading, as well as by all the phenomena that influence the shape, composition, and properties of the individual particles, as well as the size distribution and porosity of the debris bed. Debris bed coolability can be impaired by particle agglomeration, and the formation of cake and corium ingot/crusts that exceed certain dimensions, as well as by several other phenomena that reduce the water flow rate during natural convection heat transfer from the corium to the water. The risks of steam explosion and debris bed re-melting are addressed in several projects, see [5], with the most recent being APRI-8 [6]. The high uncertainties in the melt release and melt-water interaction characteristics can potentially be reduced by dedicated measures which:

- enhance the fragmentation of the melt,
- improve the coolability of the debris bed,
- reduce the risk and energy of steam explosions, and
- mitigate their consequences.

Unfortunately, measures that improve the situation with respect to some of these issues can make it worse for others. For example: better fragmentation may result in higher “efficiency” of the steam explosion.

## **5. MELT QUENCHING DURING MCCI UNDER FLOODED CONDITIONS**

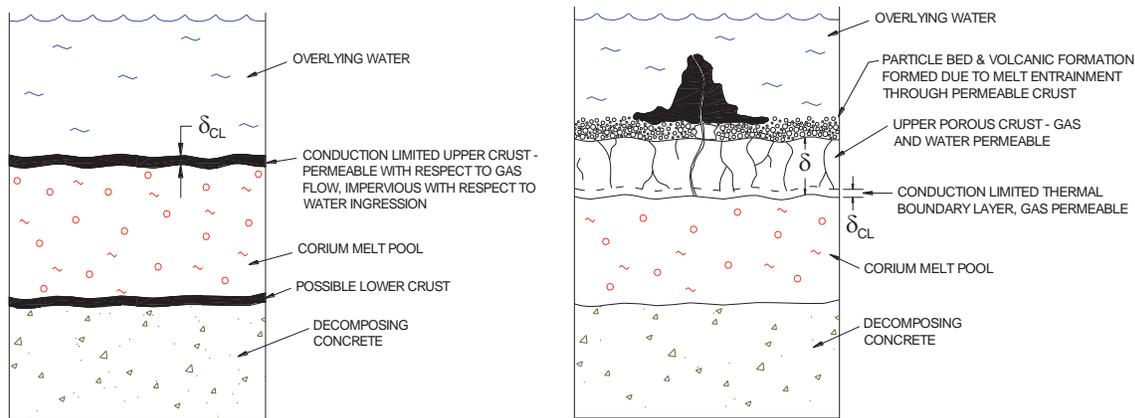
### **5.1. Historical Background**

In the wake of the Three Mile Island accident, several research efforts were made to investigate the consequences of core melt accidents. One significant question that arose as part of this investigation was about the effectiveness of water in terminating an MCCI by flooding the interacting melt from above, thereby quenching the molten core debris and rendering it permanently coolable. Based on these potential merits, ex-vessel corium coolability has been the focus of extensive research over many decades as a potential accident management strategy for current plants. In addition, outcomes from this research have also impacted the accident management strategies for some of the Generation III(+) LWR plant designs.

### **5.2. Main Functional Principles**

Corium coolability under the conditions when water is introduced atop an MCCI can be promoted by various heat transfer mechanisms, which become effective either subsequently or in parallel. In the initial bulk cooling regime, melt/water heat transfer is predominately due: to (i) radiation across the agitated (i.e., area enhanced) melt/water interface, and (ii) entrainment of melt droplets into the water overlayer. As melt temperature, downward heat transfer and melt sparging from concrete decomposition gases steadily decline, at some point, a crust will form at the surface which separates the melt from the water. Owing to the necessity of venting concrete decomposition gases, it will be characterized by some degree of porosity or cracks, see Figure 2-(a). The thickness of this crust adjusts to the thermal boundary conditions so it does not represent a thermal insulation. At this point, melt quenching can only progress if, either the melt depth lies below the minimum depth at which decay heat can be removed via conduction heat transfer to the top and bottom (~10 cm) or melt and water are able to penetrate this crust by some mechanisms that sufficiently augments the otherwise conduction-limited heat transfer process. Three main mechanisms have been identified through experiments, see Figure 2-(b).

The first mechanism is water ingress through interconnected porosity or cracks. This process relies on crack propagation through the material and, as such, is highly dependent upon the mechanical properties, since thermal stress is a key factor. This mechanism is therefore in particular relevant at low concrete (silica) content in the melt.



**Figure 2: MCCI Phenomena: (a) Conduction-limited Upper Crust at Melt Water Interface; (b) Water Ingression and Melt Eruption Cooling Mechanisms [7]**

The second mechanism is particle bed formation through “volcanic” eruptions. In this case, concrete decomposition gases entrain melt droplets into the overlying coolant as they pass through the crust. The entrained droplets then solidify in the overlying coolant and accumulate as a porous particle bed atop the crust. The third mechanism, not shown in Figure 1-(b), is the mechanical breach of suspended crusts. Such crusts can bond to the reactor cavity walls, eventually causing the melt to detach from the crust as the MCCI continues downwards as the released gases reduce the volume of the concrete as it becomes incorporated into the core melt. However, this configuration is likely not stable due to the poor mechanical strength of the crust in comparison to the applied loads (i.e., the crust weight itself, plus the weights of the overlying water pool and the accumulating dispersed material). Eventually the suspended crust is thus suspected to fail, leading to the ingression of water beneath the crust. The sudden introduction of water will provide a pathway for renewed debris cooling involving the same mechanisms. The extent to which these three mechanisms can be effective depends on various parameters, including melt depth, temperature, composition/properties, decay power, as well as on the timing of water addition.

### 5.3. Status of Validation

To reduce the remaining uncertainties a number of experimental programs had been conducted. The coolability database generated by these tests now consists of tests conducted with low temperature glycerin/liquid nitrogen simulants, high temperature stainless steel and oxide simulants, and finally experiments conducted with reactor materials at intermediate and large scale. The latter were mainly conducted at Argonne National Laboratories (ANL) as part of the MACE (EPRI) and the CCI/SSWICS projects. The key findings of these programs are summarized in [7]-[9].

The primary heat transfer mechanism credited with providing a coolable debris configuration in these experiments is volcanic eruptions, leading to a high surface area melt configuration. Melt eruptions have been predominantly observed in experiments conducted with LCS concrete, while no such eruptions were observed in tests with siliceous concrete. The single test conducted with LCS concrete (CCI-2) cooled exceptionally well, with complete quench achieved over a timescale of approximately an hour. Both water ingression and melt eruption cooling were observed. The posttest debris porosity in this experiment was very high, see Figure 3-(a), which was a key contributor to the observed coolability. Melts with a high content of siliceous concrete (CCI-3) showed much less cracking and water ingress, see Figure 3-(b). Besides showing extensive melt eruptions, the MACE tests also demonstrated that water ingression can contribute to coolability. This mechanism was further investigated in the SSWICS separate effect tests series (unheated melt, inert basemat) carried out as part of the OECD/MCCI program.



**Figure 3: Post-test debris morphology observed in selected CCI-experiments: (a) Test CCI-2 with LCS concrete; (b) Test CCI-3 with siliceous concrete**

#### 5.4 Remaining Open Issues and R&D Needs

Although some encouraging results with respect to melt quenching were obtained, it should be reminded that the underlying experiments suffer from a number of deficiencies which may reduce the robustness of the results when transferred to reactor situations like: the deviation in scale (small test-section with higher surface to volume ratio), the fact that, after solidification, the debris is no longer heated, the absence of a metallic phase, the absence of repeated melt pours, the limitation to high power and gas rates (early scenario). It is currently not possible to predict whether and how these deviations from the real situation have influenced the results in either positive or negative direction.

### 6. MELT STABILIZATION BY BOTTOM WATER INJECTION

#### 6.1. Historical Background

The COMET concept for ex-vessel melt cooling, developed at Forschungszentrum Karlsruhe, Germany (now KIT) [10] is based on water injection to the bottom of the ex-vessel corium melt. This way of water addition avoids the inherent limitations in melt-water mixing and counter-current flow inside the fragmented crust that arise when the melt is flooded from the top, see Chapter 5. Three variants of the COMET design Three COMET variants were investigated for application in new reactor concepts [11] such as the EPR™. Here two different solutions are envisaged for the location of the cooling device

Sideways of the reactor pit, which allows melt pre-conditioning and the collection of late melt releases to enable a controlled spreading onto the cooling device, as realized in the EPR™ reactor.

Below the RPV, which reduces the spreading requirements, but also the time available for melt accumulation, which is now defined by the thickness of the available sacrificial concrete layer. Optionally, the terminal coolant water level can be chosen above the residual core debris inside the RPV, thus eliminating further melt releases. This variant may be applicable to existing plants.

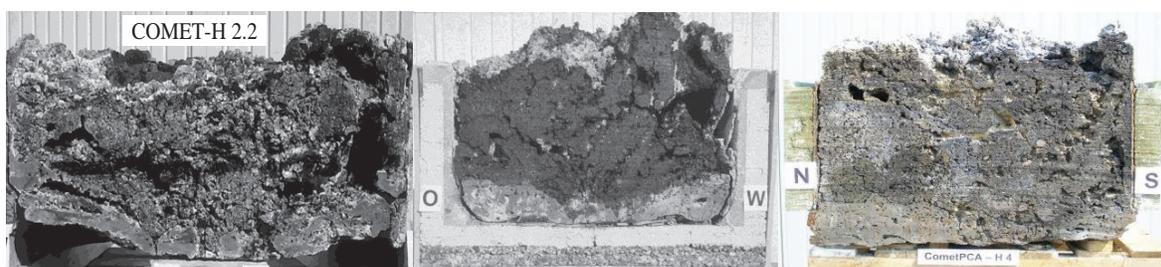
The original, first COMET variant uses an array of plastic tubes, embedded in concrete and connected to a water reservoir pressurized by a static overhead. Water is fed into the melt through the plastic tubes after the melt has eroded the sacrificial concrete layer. This injection mode yielded high resistance against uncontrolled downward melt progression. Representative test results are given in the Figure 4 (left).

The second variant replaces the array of tubes by a layer of porous, water-filled concrete CometPC (COMET Porous Concrete). The porosity of the concrete is adjusted to yield an appropriate coolant water flow into the melt. A uniform horizontal distribution of the water may be achieved by a second, high porosity concrete layer underneath. Representative test results are given in the Figure 4 (middle).

The CometPC concept was further developed to the CometPCA (Comet Porous Concrete Advanced). Due to the insertion of water channels with a regular pattern in the porous and water-filled concrete layer, the melt is penetrated more homogeneously by the water and thereby solidifies rapidly over the whole cooling area, see Figure 4 (right). This third variant combines the advantages of the injection nozzles of the original COMET concept with the water-filled porous concrete layer of the CometPC concept.

## 6.2. Main Functional Principles

The COMET concept is based on water injection into the melt layer from the bottom, yielding rapid fragmentation of the corium, porosity formation and thus coolability. The open porosities and large surfaces that are generated during melt solidification form a porous permeable structure that is permanently filled with the evaporating coolant water and thus allows efficient short-term and long-term removal of the decay heat. Representative test results are assembled in Figure 4.



**Figure 4 Post-test view of a porously solidified melt demonstrating a safe arrest of the melt in axial and in radial direction: left: COMET-H 2.2, middle: CometPC H5, right: CometPCA-H4.**

## 6.3. Status of Validation

The investigations, performed so far, have been used to optimize the COMET concepts and to define the range of applicability under reactor conditions. The COMET concept with the injection tubes is considered to be mature for reactor application. Also for the CometPCA concept, recent investigations have demonstrated its technical applicability for corium layers up to 0.5 m high. The COMET bottom cooling concept is thus able to guarantee safe arrest and cooling of the melt under ex-vessel conditions.

Several experimental series have been performed by FZK to test and optimize the functionality of the different variants of the COMET concept. Major test series were COMET-T, COMET-U and COMET-H about the basic concept with melting plugs and CometPC-H, CometPCA-H about the concepts with porous concrete. Besides COMET-U, in which cooling of  $\text{UO}_2$  rich oxide melts was successfully demonstrated, all other experiments used thermite generated, high temperature melts of iron and aluminium oxide, with addition of about 35 wt.% CaO. This admixture reduces the solidification temperature of the oxide from that of pure  $\text{Al}_2\text{O}_3$  (2323 K) to about 1670 K. Also the viscosity of the melt is decreased and is comparable with that of a corium melt after admixture of sacrificial concrete. The initial temperature of the melt amounts to about 2150 K.

In all experiments that use metal and oxide melts simultaneously, the heavier metal melt stratifies below the oxide melt, a situation which is also expected after admixture of major concrete constituents to the  $\text{UO}_2/\text{ZrO}_2$  part of corium melt. Unfortunately, no oxide/metal pair was found that matches the conditions of a lighter metal on a heavier oxide as they would exist during the initial phase after corium release. However, these conditions are expected to be represented by experiments with a pure oxide melt.

The experiments have demonstrated the high efficiency and reliability of the bottom flooding concept for the two COMET and CometPCA concepts. Key results are:

- Up to 50 cm high oxide plus metal melts are safely arrested and cooled through bottom flooding with 0.2 bar overpressure (against the predicted hydrostatic melt pressure) in the coolant water.
- A coolant water flow rate of about 2 kg/s per m<sup>2</sup> resulted in a high quenching rate of 3 MW/m<sup>2</sup>, which is about one order of magnitude above the decay power level.
- The melt is arrested at the level of the coolant inlet channels and above the porous concrete layer, and solidifies as a porous permeable structure permanently filled with water/steam mixture
- Because of the presence of the coolant water and rapid solidification of the melt, the structures adjacent to the cooling device remain cold and are not exposed to substantial loads.
- Hydrogen and aerosol production are limited to the early cooling phase. Releases end when the metal layer is solidified, i.e. after 1000 s typical.

The experiments show that the concept of water injection from the bottom results in fast cool-down and complete solidification of the melt, but also in high rates of steam and hydrogen generation.

#### 6.4. Remaining Open Issues and R&D Needs

It should be noted that, in all experiments with thermite-generated melts, only the metallic melt at the bottom was heated. In addition, though one experiment with secondary melt addition to the top during quenching has been performed, uncertainties remain regarding the effect of repeated releases and early water addition to the top (leading to the formation of surface crusts) on the fragmentation mechanism.

### 7. MELT STABILIZATION ON REFRACTORY MATERIAL

#### 7.1. Historical Background

A core catcher based on the use of refractory layers and the Passive Containment Cooling System (PCCS) are the key system to protect the containment integrity and avoid containment venting in case of severe accidents in Toshiba's EU-ABWR [12], see Figure 5. In combination with the PCCS the core catcher arrests and stabilizes the ex-vessel core melt by cooling its top and bottom surfaces. The cooling of the core melt releases large amounts of steam into the drywell of the containment. Any excessive steam is condensed in the wetwell, from where the condensate is returned to the core catcher.

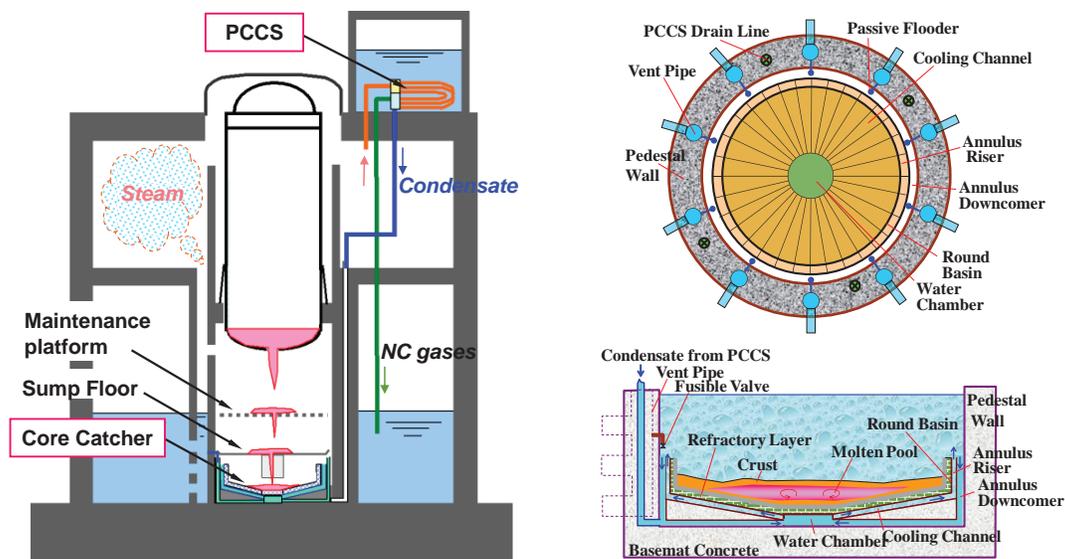


Figure 5 The Core Catcher Concept of the EU-ABWR

## 7.2. Main Functional Principles

A schematic of the core catcher concept is shown Figure 2. The core catcher is installed on the bottom floor of the reactor pedestal area below the RPV in the containment, and covers all pedestal floor to capture and contain the ejected core melt. The core catcher consists of a round basin, lower inclined cooling channels axisymmetrically arranged, an annulus riser, an annulus downcomer and a central water chamber. This axisymmetrical structure promotes the formation of a uniform distribution and cooling of the core melt. The core catcher has a comparatively large diameter of 10m. The established large surface-to-volume ratio of the core melt results in an effective cooling [13]. The refractory layers are installed on the surface of the basin to prevent failure of the steel basin due to over-temperature and erosion. The refractory layers consists of a zirconia layer and an alumina layer. When ejected into the pedestal area from the RPV, the core melt will first fall on the sump floor above the core catcher. Due to its high temperature ( $>2500\text{K}$ ) the core melt will penetrate the floor in a few minutes and flow into the core catcher. As, at this time, the core catcher is dry, so energetic fuel-coolant interactions (FCI) are prevented.

The cooling water is initially supplied from the suppression pool via the passive flooders. Each passive flooder is connected to a drywell-wetwell connecting vent pipe, and has a fusible valve at the end. The passive flooder will not open until the core melt has arrived. The fusible valves will open when the temperature in the pedestal area increases and subsequently reaches the melting temperature of the fusible material. The fusible material will be selected with sufficiently high melting temperature (typically greater than  $450\text{K}$ ) to avoid unnecessary opening during design basis LOCA, and sufficiently low melting temperature (typically less than  $540\text{K}$ ) to avoid over-temperature in the containment.

After the core melt ejection, the fusible valves of the passive flooder are predicted to open within several minutes, and the suppression pool water will flow into the peripheral annulus downcomer of the core catcher. After the core catcher flooding, the core melt will be cooled from the top by water and from the bottom by the lower inclined cooling channels. In the inclined cooling channels natural circulation will be established within channels and downcomer thus establishing effective cooling of the core catcher. In the long term the cooling water is resupplied via the PCCS condensate drain. For more details see [14].

## 7.3. Status of Validation

During its operation the core catcher will be exposed to various kinds of load. Table 1 shows the expected loads and the corresponding validation. The goal of the validation is to show that the core catcher withstands all short term and long term thermal and structural loads.

In the short term, jet impingement, jet impaction and steam explosion would be major loads. These loads could be coped with the structural design. In the long term, melt-through, creep failure and thermal stress would be major loads. In order to confirm the integrity against the long term loads, the integral thermal analysis code is developed to know the temperature profile in the core melt and the core catcher structure, including thermal transient models for heat conduction, heat transfer, crust growth/shrink and thermal erosion of the structures, incl. the protective material.

## 7.4. Remaining Open Issues and R&D Needs

Some analytical and experimental works have been conducted to validate the core catcher design. Through the works, the core catcher was shown to have sufficient capability for core melt retention. There is no remaining issue in the conceptual design phase. But, some additional works in the detailed design will be necessary, including the evaluation of debris clogging in the flow path and the reflection of some new knowledge on the interaction between melt and refractory materials. The latter includes optimizing the residual thickness of the refractory layer at which the contradictory requirements regarding layer stability and effective heat conduction can be matched.

**Table 1 Main Loads on the Core Catcher and the Status of Validation**

Loads		Status of Validation
Short-term	Jet Impingement	Jet impingement by a high speed melt jet in case of High Pressure Melt Ejection (HPME) can be excluded by the management of RCS depressurization. The jet impingement during low pressure melt ejection is considered in the design base for the refractory layer.
	Jet impaction	Core melt is ejected from the RPV will first hit the structures of platform and sump floor. Despite this, free-falling melt impact is conservatively assumed in the analysis using FEM. The structure is confirmed to withstand the jet impaction.
	Steam explosion	Risk of steam explosion is minimized by the “dry cavity”. A steam explosion load of 90 kPa-s is assumed, and the structure is confirmed to withstand this load.
Long-term	Melt-through	If the structure temperatures including the refractory layer and the steel basin reach their melting temperatures, the structures would be eroded and melted through. The refractory layer is designed to prevent any melt-through, as confirmed by thermal analysis.
	Burnout	The cooling channel configuration was confirmed to provide sufficient thermal margin against burnout under the expected conditions by circulation tests and integral analysis.
	Creep failure	It is confirmed by thermal analysis that the refractory layer contributes to prevent high temperatures and creep failure of the steel basin.
	Thermal stress	The thermal stress and thermal deformation of the structure caused by the core melt was evaluated by FEM analysis, the structure is confirmed to prevent any mechanical failures.

## 8. CRUCIBLE-TYPE CORE CATCHER BELOW THE RPV

### 8.1. Historical Background

The VVER-1000 and VVER-1200 reactors apply a retention concept [15] based on a secondary outside-cooled vessel located below the RPV. Main reasons contributing to the choice for this solution were: (i) the gained experience during development and justification of the IVR concept for the VVER-640 reactor, (ii) a significant volume available in the reactor pit underneath the RPV, (iii) the lack of an adjacent compartment with sufficient surface area for melt spreading, and (iv) the large mass of water in the containment with the possibility to use gravity-driven cavity flooding. The developed crucible-type core catcher underneath the RPV combines the principles of in-vessel melt retention, i.e. passive water cooling of the vessel, with the control of corium properties by means of sacrificial materials (SM) addition. This combination leads to a significant reduction of heat fluxes from the core catcher vessel to the cooling water and additional safety margins in comparison to a corresponding in-vessel retention solution.

### 8.2. Main Functional Principles

The developed design is sketched in Figure 6a. It fulfills the following main functions:

- Collection and enclosure of the corium inside the volume of the catcher vessel (5).
- Corium coolability and retention vessel integrity by external cooling and natural convection (4).
- Prevention of secondary criticality.
- Minimization of fission product release into the containment atmosphere.
- No additional generation of hydrogen or other non-condensable gases.

After RPV (1) melt-through, the lower plate (2) directs the corium to the core catcher through an axial conical hole. The internal space of the catcher vessel is partially filled with SM (6) which is a combination of sacrificial steel and fusible oxide ceramic of low density. The sacrificial ceramic (Fig. 2) contains  $Al_2O_3$ ,  $Fe_2O_3$  and functional additives including oxides of Gadolinium [15, 16]. The addition of the SM to the corium allows to control the melt properties and to establish suitable conditions for the operation of the core catcher [16] in the short and long term, by the:

- Reduction of the density of the oxidic corium, the resulting top location of the oxide layer prevents the focusing effect and reduces the steam explosion risk during water top flooding.
- Dilution of both oxide and metal melts and increase in melt volume and lateral heat transfer surfaces resulting in a decrease in specific volumetric power in the melt and thus in lower heat fluxes to the cooling water.
- Endothermic effect of corium/SM interaction and increased contents of fusible compounds in the system results in decreasing melt and liquidus temperatures and reduced FP evaporation rates.
- Addition of the neutron absorber  $Gd_2O_3$  which ensures subcriticality after water addition.
- Oxidation of active reducers, primarily Zr, contained in the melt by the added iron oxide resulting in a strong reduction of Zr oxidation by water and hydrogen generation.
- Addition of stable Sr isotope into the SM to suppress releases of radioactive 89,90Sr isotopes.

After corium accumulation and interaction with SM, top flooding of the molten pool by water is activated to cool down the pool surface and to finally suppress radiant heat flux and fission product release.

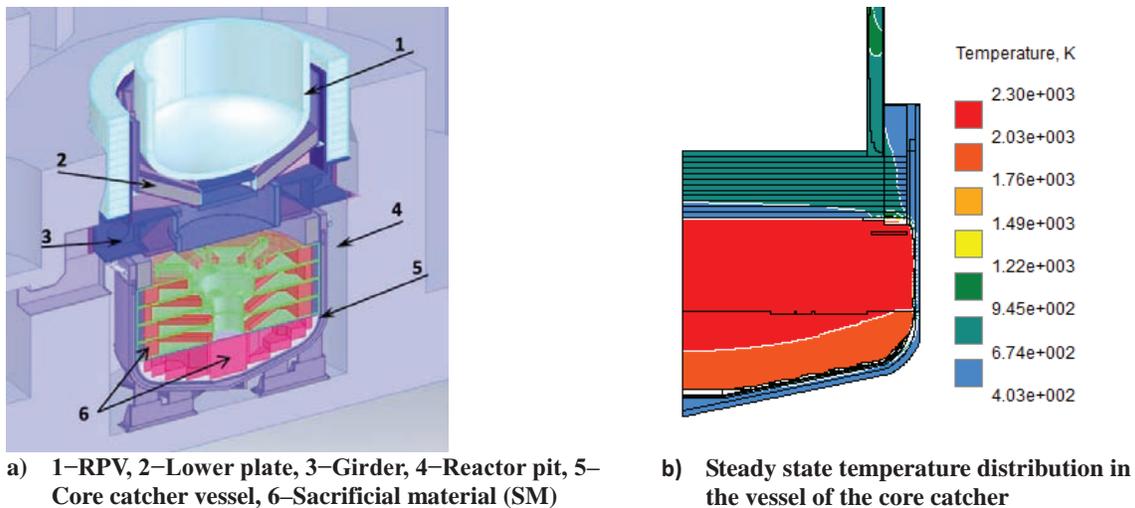


Figure 6 Core catcher for VVER-1200

### 8.3. Status of Validation

The concept and basic design of a crucible-type core catcher are described in details in [16]. More information about the oxide SM can be found in [17] and the papers referred in [16]. In these works, theoretical, numerical, and expert analyses of alternative materials are provided. Corium properties and the various phenomena during corium interaction with the core catcher materials were investigated within the following clusters of experimental works by collaboration in national programs and internationally as part of related ISTC and OECD projects:

- Interaction of oxidic and metallic melts with oxide SM and the related aerosol and FP release
- Melt oxidation kinetics and phase diagrams of the resulting multicomponent corium systems.
- Interaction of suboxidized corium with molten steel and the water-cooled steel vessel wall.
- Water flooding oxide and metal melt.
- Behaviour of thermal protection screens under thermal loads from corium melt surface.
- Critical heat fluxes on the vertical and concave downward surfaces of the core catcher vessel.

Comprehensive analyses and experimental studies have confirmed the efficiency of a crucible-type core catcher for SAM concept of NPPs with VVER-1000 and 1200.

## 8.4. Remaining Open Issues and R&D Needs

Large experience of design and construction works and new knowledge about severe accident phenomena and corium behavior was accumulated since the first catcher was constructed at Tianwan NPP, China. Computer codes, materials, manufacturing technology of structural components, assembling technology and other elements have been significantly improved. Further developments taking benefit of these improvements are under way, e.g. to improve system economy. Besides this, the use of coupled thermodynamic / thermohydraulic modeling of corium melt retention in the reactor vessel and in the ex-vessel core catcher is one of prioritized future approaches, which can significantly reduce uncertainties in the safety analysis used for justification of these SAM measures.

## 9. CRUCIBLE-TYPE CORE CATCHER IN A LATERAL COMPARTMENT

### 9.1. Historical Background

During the developmental phase of the European Pressurized water Reactor EPR™, Siemens-KWU/AREVA has investigated the technical and technological feasibility of various concepts for core melt stabilization. The decision for an outside-cooled crucible concept was finally made because of the robust performance and the related ease of validation. Reasons for not placing the crucible right underneath the RPV were the high predicted loads during RPV-failure and the specifics of the existing building structure.

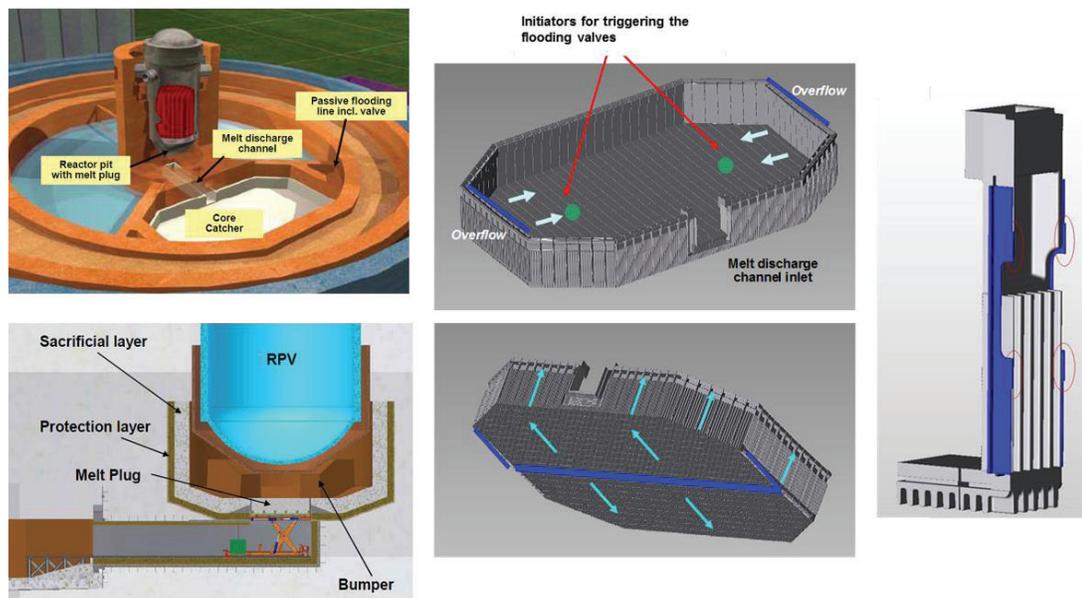
### 9.2. Main Functional Principles

The function of the EPR™ CMSS, see Figure 7, is based on a two phase approach [18]. During the 1st phase the melt is accumulated and conditioned in the reactor pit. Then, in the 2nd phase, the collected melt spreads into the core catcher in a single pour. There it is cooled by passive water overflow from the in-containment refueling water storage tank (IRWST). The decay heat is removed from the melt either by water heat-up or boiling. Both, the reactor pit and the core catcher are kept initially dry to eliminate the risk of energetic steam explosions during melt arrival.

The introduction of a temporary phase of melt retention in the reactor pit responds to the prediction that the release of molten material from the RPV will, most likely, not occur in a single pour but over a certain period of time, in the form of several distinct pours. Without prior accumulation, this would result in undefined conditions for the relocation of the melt into the core catcher. The accumulation function is realized by a layer of sacrificial concrete that covers the floor and sidewall of the reactor pit. The sacrificial material includes iron oxide, to oxidize the Zr and lowers the melts liquidus temperature, and silica, to make the melt more viscous and inhibit steam explosions during the later flooding. A second, protective (zirconia-brick) layer around the sacrificial concrete makes the accumulation function insensitive to uncertainties in the progression of the MCCI. There is only one way for the melt to exit the pit: it must penetrate the concrete layer of the melt plug in the center of the pit bottom, as this is the only location where the concrete is not backed up by the protective layer. At this time the melt will have incorporated most of the provided sacrificial concrete, which makes the composition and temperature of the melt very predictable. This narrows the spectrum of melt states and makes all subsequent steps independent of the preceding accident scenario.

After penetrating the pit bottom the melt is guided through the transfer channel into the core catcher. As the outflow is above the maximum melt level, practically all melt will be released from the channel. The core catcher structure is assembled from thick cast iron elements, which can withstand any transient loads during initial melt contact. The modular structure further limits thermal deformation and thus make the integrity and proper cooling function insensitive against the uncertainties in the melt configuration. While spreading inside the core catcher the melt destroys initiators that trigger the opening of redundant passive flooding valves. Their design ensures that, once they are open, they will stay open indefinitely.

The overflowing water from the IRWST is distributed via a central channel embedded in the concrete below the cooling structure, see Figure 7. Then it fills the volume around the core catcher and finally spills over onto the surface of the melt. All steam generated during melt quenching and cooling is released into the containment where it is condensed by the sprays of the containment heat removal system (CHRS). The water level in the spreading compartment ultimately rises to the equilibrium level with the IRWST. As this submerges the melt discharge channel and the bottom part of the reactor pit, local melt remnants, potentially left behind along the way will also be cooled. In parallel, to this overflow mode, the CHRS can also inject water below the core catcher, which floods the reactor pit and RPV up to the loop lines and which prevents further steaming into the containment.



**Figure 7 EPR™ core melt stabilization system: Overview (left-top), Components for temporary melt retention in the pit (left-bottom), Cooling structure (right).**

### 9.3. Status of Validation

The CMSS of the EPR™ reactor was developed under the premise to keep the necessary research and development effort low. Situations and phenomena that involve a high complexity and/or are insufficiently quantifiable were avoided, if necessary by the implementation of dedicated design measures which influence the related processes towards higher predictability. Examples are the: avoidance of conditions that can potentially lead to energetic steam explosions, and the admixture of sacrificial material which ultimately dominates the state and properties of the melt independent of the preceding scenario. For each of the key processes an adequate data base is available [19], which is supported by dedicated experiments or in the frame of national and international research and development projects.

### 9.4. Remaining Open Issues and R&D Needs

The EPR™ core melt stabilization concept has successfully passed the licensing procedures in several countries. Therefore, no further R&D is required for validating the concept itself. However, the current design basis still contains significant conservatism, because at the time when the features were fixed the status of R&D was less evolved and corresponding additional margins were implemented. If better corresponding data are available, these conservatisms can be removed and more lean solutions be adopted.

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