Effects of mechanical design measures for the EPR melt retention concept

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ABSTRACT

The phenomena, which have to be considered in the EPR concept for core melt stabilization within the containment are mainly related to melt discharge, spreading, retention and long-term cooling. In addition, specific phenomena like melt dispersal after RPV failure and ex-vessel melt-water-interaction have to be dealt with. For the elaboration of mechanical design measures provided to stabilize the melt, boundary conditions may occur which could pose extremely high thermal and mechanical loads on the structures. Also, principally, a large number of different scenarios have to be considered, with an also high number of different specific boundary conditions. In order to deal with this challenge an approach is applied which is based on influencing the course of severe accident scenarios thereby the related boundary conditions by means of dedicated design measures. As a result, plant states and conditions can be generated, which are well defined and for which either assured knowledge exists or which can be eliminated by further R&D. This approach has the potential to develop mitigation measures with a high confidence in the effectiveness of the provisions. The paper describes the issues to be considered, the design measures proposed and the conditions resulting from these design measures. This approach can minimize “knowledge driven” R&D in favor of “end-user driven” R&D, with the effect of being able to present a concept within an acceptable time and reasonable cost frame.

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.

POTENTIAL APPROACHES FOR THE SELECTION OF DESIGN MEASURES

Mitigation means for design basis accidents can take benefit from the fact that the geometry of the components is more or less intact and that the conditions are not so far from normal operating conditions. In severe accident scenarios the situation is very different. The corresponding conditions are characterized by the fact that the integrity of important components, like the fuel assemblies and the RPV, are lost and that the conditions may differ completely from operating conditions. As an example temperatures can become extremely high and exceed the limits or which the materials used in plant design are specified for, or even for which material data are existent. In addition, a large number of different scenarios and boundary conditions must be dealt with.

The designer who has to develop concepts for the mitigation and control of the consequences of severe accidents can, in principle, apply two different approaches for the specification of appropriate design requirements.

One approach is to envelop the entire range of scenarios and potential loads and to define this as a basis for the mitigation measures. For many cases this approach may be an appropriate procedure. Yet for the severe accident issue considered here it has two important disadvantages: first, one has to be sure that the complete range of potential scenarios and resulting loads is covered. This is highly uncertain since the phenomena and problems to deal with have a very low probability and therefore the selected scenarios are more or less arbitrary. In addition such an “enveloping load approach” may lead to extreme requirements on the technology to be provided and to extremely expeditious design solutions which can heavily burden the capital cost of the plant.

The other approach – which shall be nominated as “controlled plant-state approach”, and which is described in more detail in this paper - intends to influence, from the beginning, the type of the severe accident scenario and the corresponding course of events. The idea is to generate states, which are characterized by rather well defined conditions and which are within the range of applicability of the applied technology. For these states either assured knowledge must already exist or must be acquirable with limited specific R&D. As a consequence, it is possible to evaluate the effectiveness of the developed mitigation measures with high confidence.
For this kind of approach, the designer must be involved in the entire process of development, in order to be able to identify possibilities for design provisions that may reduce the necessary R&D effort. We are strongly convinced that this approach leads to solutions which, from the point of view of technology and overall plant design, are more appropriate and do have the potential of minimizing the burden on the capital cost of the plant.

CHARACTERISTIC FEATURES OF THE APPROACH PROPOSED TO BE FOLLOWED

The task of elaboration of a concept for the control of any severe accident phenomenon is subdivided into the following steps:

1. Identification of the governing issues
2. Identification of the dependence between relevant parameters
3. Definition of design conditions and requirements

The characteristic of the proposed approach is to implement design provisions for the first two steps in order to influence the third one, namely the conditions for which design requirements have to be defined.

In the first step, the provisions shall either reduce the number of problems or prevent conditions, which may lead to extensive design efforts, or at least to a minimization of thermal and mechanical loads. In the second step, design provisions shall reduce the importance of critical parameters or influence the required extent of analysis of individual parameters and consecutively the required R&D work.

The result of the proposed design measures is a reduction of range of conditions that have to be mitigated. Also, the design conditions and requirements for the measures to be introduced can now be realized on the basis of proven technology and appropriate cost.

In order to be able to identify governing issues and parameters that can be influenced, a close cooperation between R&D teams, analytical experts, and the designers is necessary. It is evident that this approach must be iterative as the situation may change by the ongoing generation of R&D results.

APPLICATION OF THE APPROACH FOR THE MELT RETENTION CONCEPT

In order to retain and stabilize a core melt within the containment, the problems, which principally have to be dealt with are:

- melt discharge from the reactor pressure vessel
- spreading of the melt
- long-term melt stabilization

Each of these problems has a certain amount of sub-problems which all have an influence on the core melt mitigation concept. Numerous questions have been raised which may result in extended and time consuming efforts for both R&D and design. As examples, some of these questions are as follows:

- What is the mode of corium release from the RPV? (Metal or oxide jet under pressure; low or high flow rate pouring; liquid carrying solid debris; stepwise discharge)
- What portion of the melt will be dispersed during the discharge process?
- What is the effect of ex-vessel steam explosions on the stabilization of the melt?
- What kind of spreading process can be expected and how is it influenced by late reflooding?
- Is there a potential for melt immobilization, resulting from stepwise melt discharge?

We are convinced that all these questions can be answered satisfactorily only if design measures are applied to influence the course of the entire process starting from melt discharge up to the and finally stabilized corium. The major problems, specific measures and the corresponding effects and influence on the process are described below.

GOALS AND PRINCIPLES FOR SELECION OF MECHANICAL DESIGN MEASURES

The measures 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 concept proposed for the EPR for stabilization of a core melt within the containment and for maintaining its integrity is based on the idea to spread the corium on a large surface and cool it with water from the top. A dedicated compartment is provided for spreading which is located lateral to the reactor pit and separated from by a melt plug. The plug will passively be destroyed by the melt (Fig. 1).

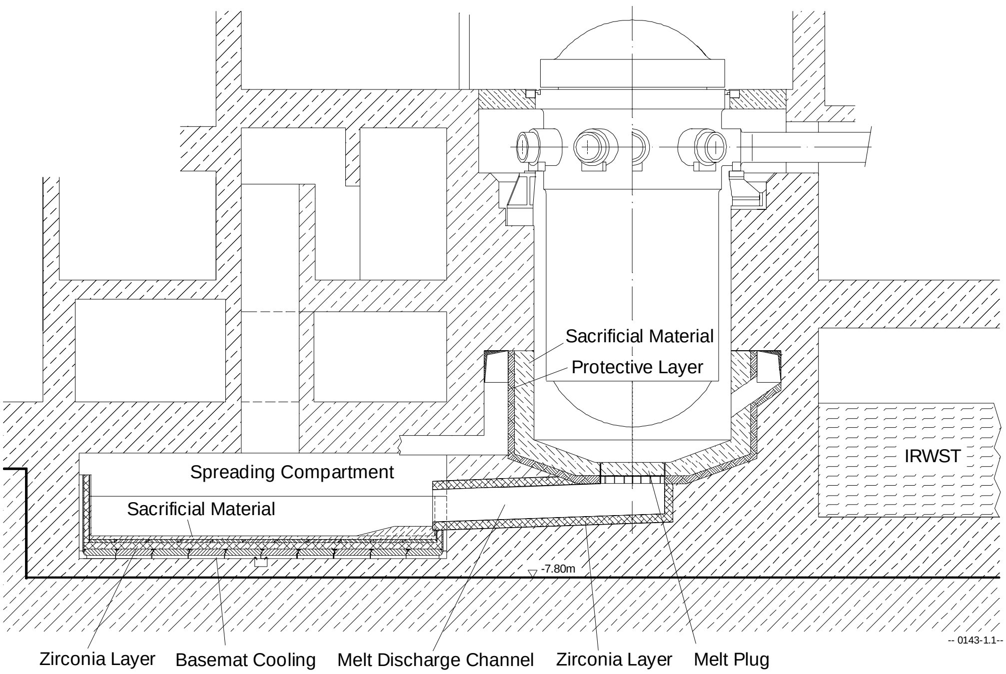

Fig. 1: Overall arrangement of spreading concept

This spatial separation between the melt release location and the retention device is one of the main features of the spreading concept (Fig. 2). After the failure of the Reactor Pressure Vessel (RPV), no immediate discharge of the corium onto the spreading area shall occur. Instead, the released molten debris will be retained temporarily in the pit to ensure that most of the inventory will be available for spreading.

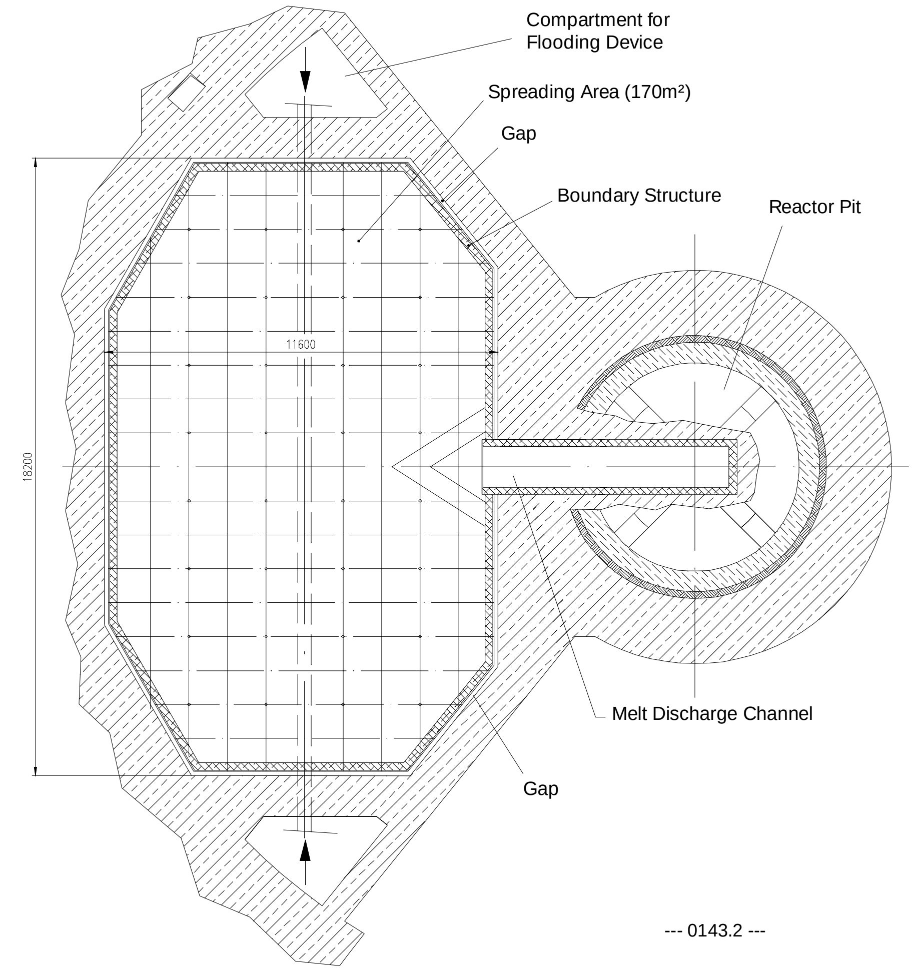

Fig 2.: Spreading area

The spread corium triggers the opening of valves, which provides a passive flooding of the melt with water drained from the IRWST. Before it pours on top of the melt the water first passes a cooling structure provided at the bottom of the spreading area. The cooling system is required to prevent a potentially unacceptable long-term heat-up of the basemat concrete structure. The top and bottom cooling will be active once the dedicated Containment Heat Removal System (CHRS) is available.

MELT DISCHARGE FROM THE REACTOR PRESSURE VESSEL

Of the three problems: RPV melt-through, spreading and melt stabilization, which have to be covered by the melt stabilization concept, RPV melt-through and the effects associated with it have the highest degree of uncertainty and can thus generate the most severe requirements. Some of the relevant issues are: melt dispersal, ex vessel steam explosion, effects of melt jet and thermal and mechanical loads. In order to cope with all these phenomena under potentially different conditions, the following basic requirements were formulated:

- High pressure RPV melt-through must be prevented
- There shall be no water within the reactor pit at time of RPV melt-through
- the location of melt stabilization shall be separated from the reactor pit

These decisions require the following specific design measures:

- Installation of dedicated devices to guarantee the depressurization of the primary circuit in case of a severe accident
- Prevention of water ingress into the reactor pit by provision of a specific design for the ex-core instrumentation together with sealing measures
- Arrangement of a spreading area in a dedicated compartment lateral to the reactor pit

The specific arrangement of the spreading area and the conditions to be provided for melt spreading require a temporary collection of the melt within the reactor pit. This is assured by sacrificial concrete in the lower part of the pit wall and a plug, which sits at the entrance of the transfer channel between reactor pit and spreading area (Fig. 3). The plug consisting of a concrete covered steel plate provides sufficient thermal-mechanical resistance to withstand the melt for a specified minimum time period (Fig. 4).
The temporary retention has the benefit to assure that most of the melt is collected before spreading. As a by-product the melt can be conditioned by the incorporation of sacrificial concrete. Its erosion and mixing with the melt leads to a change in chemical composition and a decrease in melt temperature. Together with the sacrificial material provided in the spreading room, it ensures suitable melt conditions at the time of contact between melt and protective layer.

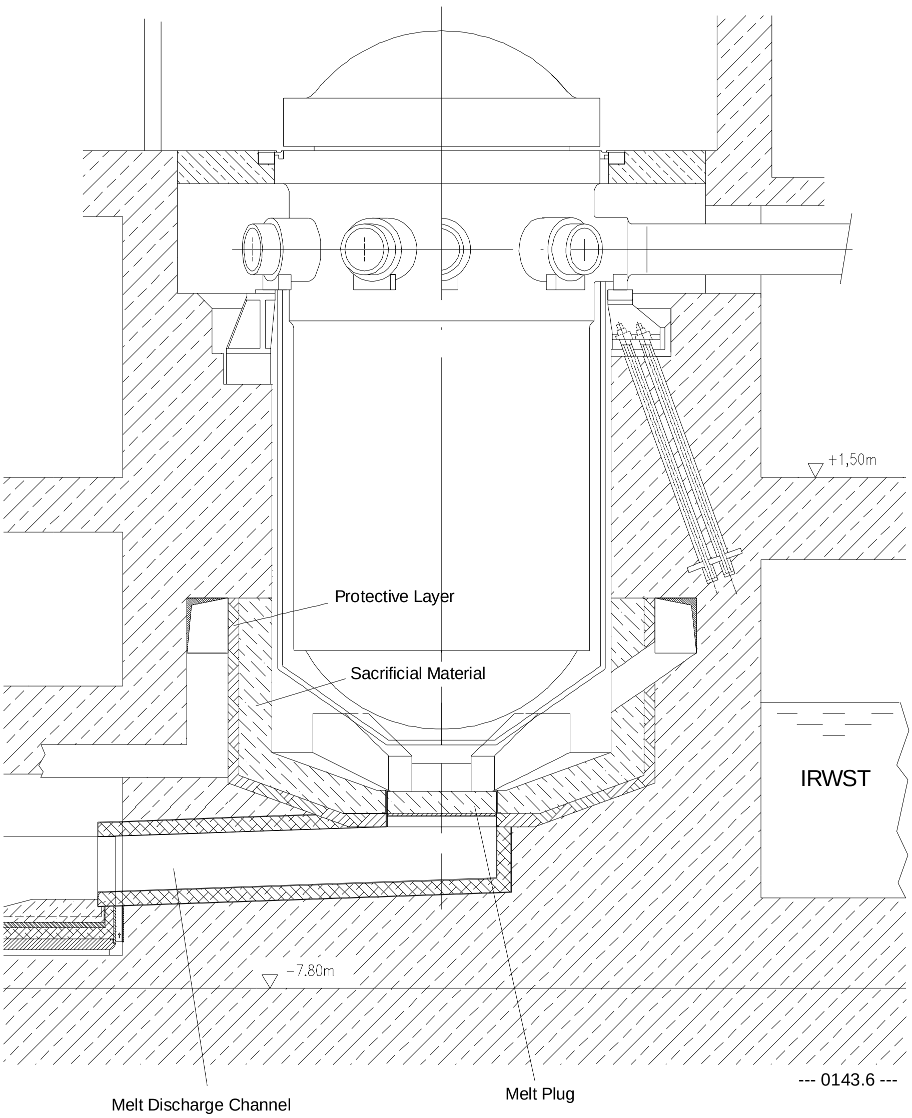

Fig. 3: Reactor pit

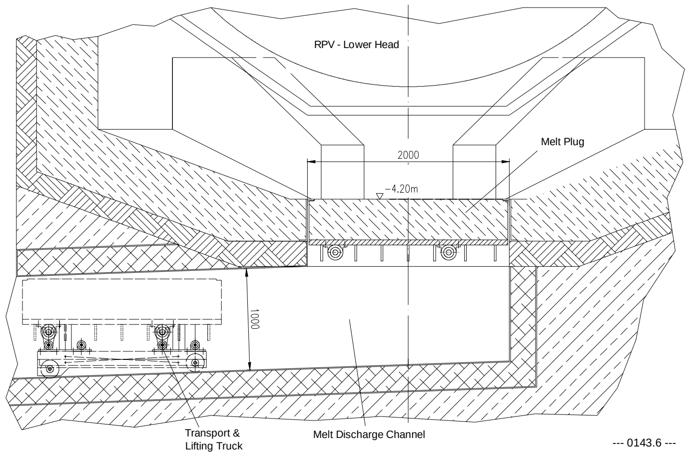

Fig. 4: Plug and transfer channel

For the problems resulting from melt discharge from the reactor pressure vessel the most relevant sub-problems are summarized in the following table, together with the provided design measures and the conditions resulting from such design measures.

Problem	**Design measure**	**Conditions resulting from design measures**
High pressure RPV melt-through	Provision of a dedicated Severe Accident depressurization device	Clearly defined depressurized state of the primary system at RPV meltthrough
RPV failure mode and resulting mechanical and thermal loads	Separation of spreading area from reactor pit	Separation of functions: reactor pit affected from short term thermal and mechanical loads; spreading area affected from long term thermal loads
Melt jets with unacceptable erosion of structures (f. i. plug)	Provision of sacrificial and protective material within the lower part of the reactor pit;	Unacceptable erosion from jets is prevented
Melt dispersal	RPV failure pressure reduction by means of a dedicated depressurization device; prevention of open flow channels to containment dome	Tolerable dispersal portion
Steam explosion within reactor pit	Prevention of open penetrations with potential of water accumulation within reactor pit as result of LOCA	Dry reactor pit, no steam explosion risk at melt discharge
High mechanical load impact on bottom structure of the pit	Provision of concrete fins at bottom of reactor pit	No direct contact between RPV bottom and plug possible; limitation of potential RPV fall-height
Sequential pours of melt from RPV with potential of melt accumulation and non-complete spreading	Separation of reactor pit from spreading area by means of a plug until discharge is complete	Collection of the melt within reactor pit; discharge into spreading compartment in one pour and of complete spreading; melt conditioning

MELT SPREADING

The spreading compartment provides an area of about 170 m² to contain the melt after failure of the melt plug. Melt is discharged through a channel and spread on this area. The channel is expected to be in contact with the melt only during the spreading process. Nevertheless a protective layer from zirconia is provided in order to prevent a contact between melt and the structure concrete. For a uniform distribution on the spreading area it is favorable to achieve a sufficiently low viscosity of the melt and to avoid the interaction between melt and large amounts of water in the spreading area. While conditioning is reached by addition of sacrificial concrete in the reactor pit the accumulation of water in the spreading compartment is avoided by restricting its connection to adjacent compartments and by providing protective walls which prevent water ingress. Thus only a small amount of water can be present due to steam condensation on the walls inside the compartment. The resulting maximum height of condensate is only one or two centimeters, which is insufficient to cause adverse effects.
The problems concerning melt spreading and the corresponding solutions are summarized in the following table:

Problem	Design measure	Conditions resulting from design measures
Spreading under water with potential energetic melt/water interaction	Spreading area within separate compartment; walls to protect water influx	Water inflow into spreading compartment resulting from LOCA not possible
Insufficient spreading due to low melt discharge flow rates	Provision of closed reactor pit with temporary resistance against thermal loads	Accumulation of complete melt within reactor pit prior to spreading; possibility for melt conditioning by provision of sacrificial material
Insufficient spreading due to material composition and thermal conditions	Provision of temporary melt retention within reactor pit and sacrificial material	Mixture of melt and sacrificial material at temperature with sufficient low viscosity

MELT STABILIZATION

Long term stabilization of the melt is achieved by melt spreading on a temperature resistant zirconia layer followed by flooding, quenching and cooling from the top. Since the stability of the protective layer is crucial for the concept, potential thermal-chemical interactions, which may challenge its integrity, are avoided by a number of diverse measures (Fig. 5), namely by the provision of:

- A sacrificial concrete layer as the top layer in the spreading compartment, the incorporation of which results in a layer inversion by reducing the density of the oxidic corium below that of the molten metal. This prevents a direct contact between oxidic corium and protective layer. This layer provides redundancy to the sacrificial concrete layer installed in the pit.
- A sacrificial metal layer underneath the concrete to ensure the presence of a metallic melt at any location, independent of the characteristics of the spreading process. The slow melt-down of the steel layer guarantees a gradual heat-up of the zirconia;
- A cooling system below the zirconia layer, which- besides keeping the temperatures in the structural concrete low – prevents any postulated downward melt progression.

Flooding of the melt is achieved by the opening of valves, which are passively the initiated by the melt itself. Water from the IPWST floods the spreading compartment and the melt surface via the cooling structure and a circumferential gap, which is provided between the lateral structure of the core catcher and the compartment walls.
The basemat cooling device is integrated in the system for melt flooding and containment heat removal. The water is provided either passively by gravity from the IRWST, or actively by the containment heat removal pumps. In case of passive cooling, the heat is extracted from the melt by evaporation of the saturated water pool in the spreading compartment into the containment atmosphere. In case of active cooling, the spreading compartment is fully flooded, and the overflowing subcooled water flows back into the IRWST. By the suppression of steaming from the spreading compartment, long term atmospheric conditions in the containment, and zero leakage from the containment are achieved (Fig. 6).

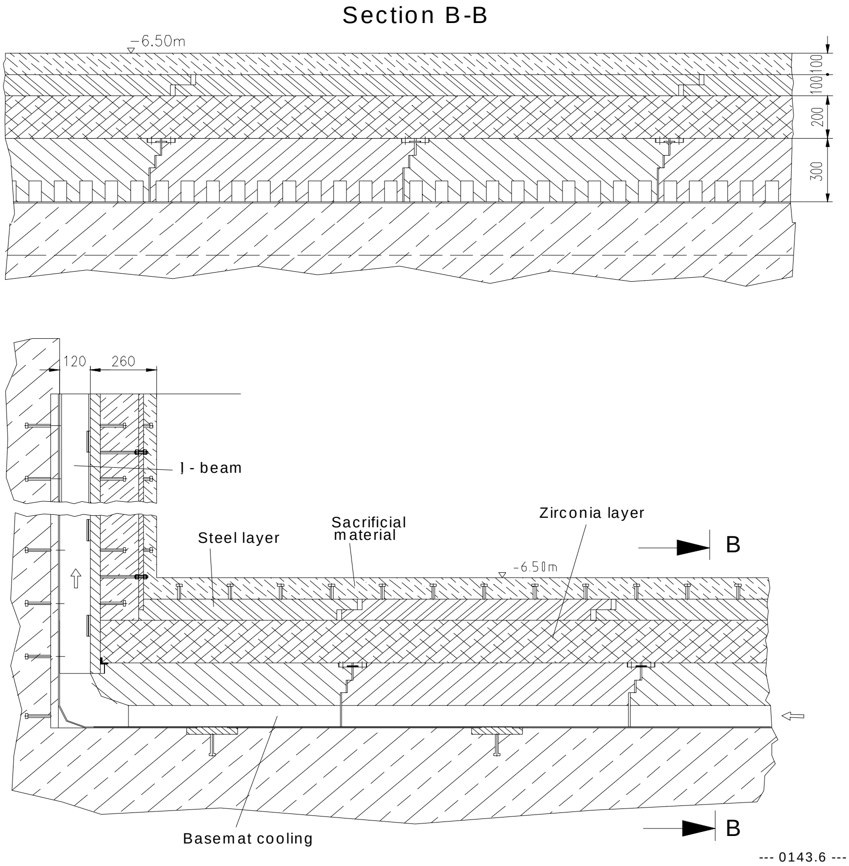

Fig. 5: Layer arrangement

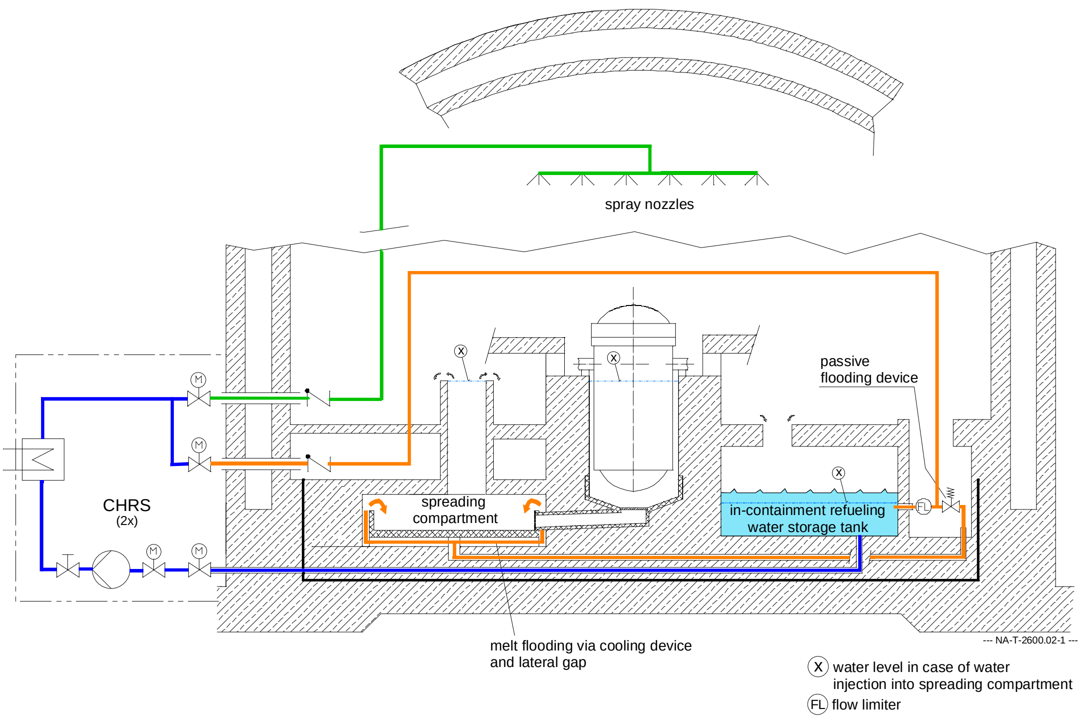

Fig. 6: Integrated CHR and basemat cooling system

Major problems, envisaged design measures and the resulting conditions are described in the following table:

Problem	Design measure	Conditions resulting from design measures
Interaction of melt and basemat concrete	Provision of sacrificial and protective layers and melt cooling from above and below	Stabilization of melt on spreading area above the protective layer
Risk of high energetic melt water interaction caused by flooding of the melt from above	Limitation of flow rate and flooding via the whole circumference of the spread melt; delay time after flooding initiation	Contact between water and oxidic melt at low flow rates results in crust generation
Thermal-chemical dissolution of the protective layer	Provision of sacrificial material to change melt conditions and of cooling underneath the protective layer	Oxidation of metallic zirconium; inversion of layering of the oxidic and metallic melt fractions; reduction of melt temperature; thermal stabilization of protective layer
High temperatures in the basemat concrete	Provision of cooling underneath the protective layer	Basemat concrete temperatures can only reach coolant water temperatures at the maximum

CONCLUSION

The result of the development work performed up to now for the EPR shows that a “controlled plant-state approach” leads to a sound concept for the stabilization of the melt [2,3]. For the development of such a concept both knowledge driven and end user driven R&D work is necessary to be performed. Yet concerning the amount of R&D effort, the chosen approach minimizes knowledge driven R&D work in favor of end user driven R&D, with the effect of being able to present a solution within acceptable time and a reasonable cost frame.

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