MDEP Technical Report
TR-VVERWG-04

Related to: VVER TESG SA activities

Technical Report on Core Catcher

Participation

Regulators involved in the MDEP working group discussions:	HAEA (Hungary), AERB (India), NNSA (CPR), Rostechnadzor (RF), NDK (Turkey), STUK (Finland)
Regulators which support the present report	HAEA (Hungary), AERB (India), NNSA (CPR), Rostechnadzor (RF), NDK (Turkey), STUK (Finland)
Compatible with existing IAEA related documents:	Yes

Introduction

1.1 Objectives of the report

Main objective of the report is to create a basis for a common understanding of features of design, safety limits and conditions of the core catcher to define safety concerns and to discuss the possibility of the common approach for licensing.

1.2 Motivations for choosing ex-vessel over in-vessel melt retention strategy in new generation VVERs

Basically there are two types of melt retention strategies based on the planned location of the stabilization of the corium: in-vessel melt retention and ex-vessel melt retention.

In the case of in-vessel melt retention the outside surface of the reactor vessel is cooled by circulated water. The advantage of the in-vessel melt retention is that the corium remains in the reactor vessel, therefore the loads on the containment as well as the risk of fission products release to the environment are smaller. Taking into account relatively high power density in AES-91 and AES-2006 and high uncertainties in assessment of corium behavior, this strategy was declined for new VVER projects.

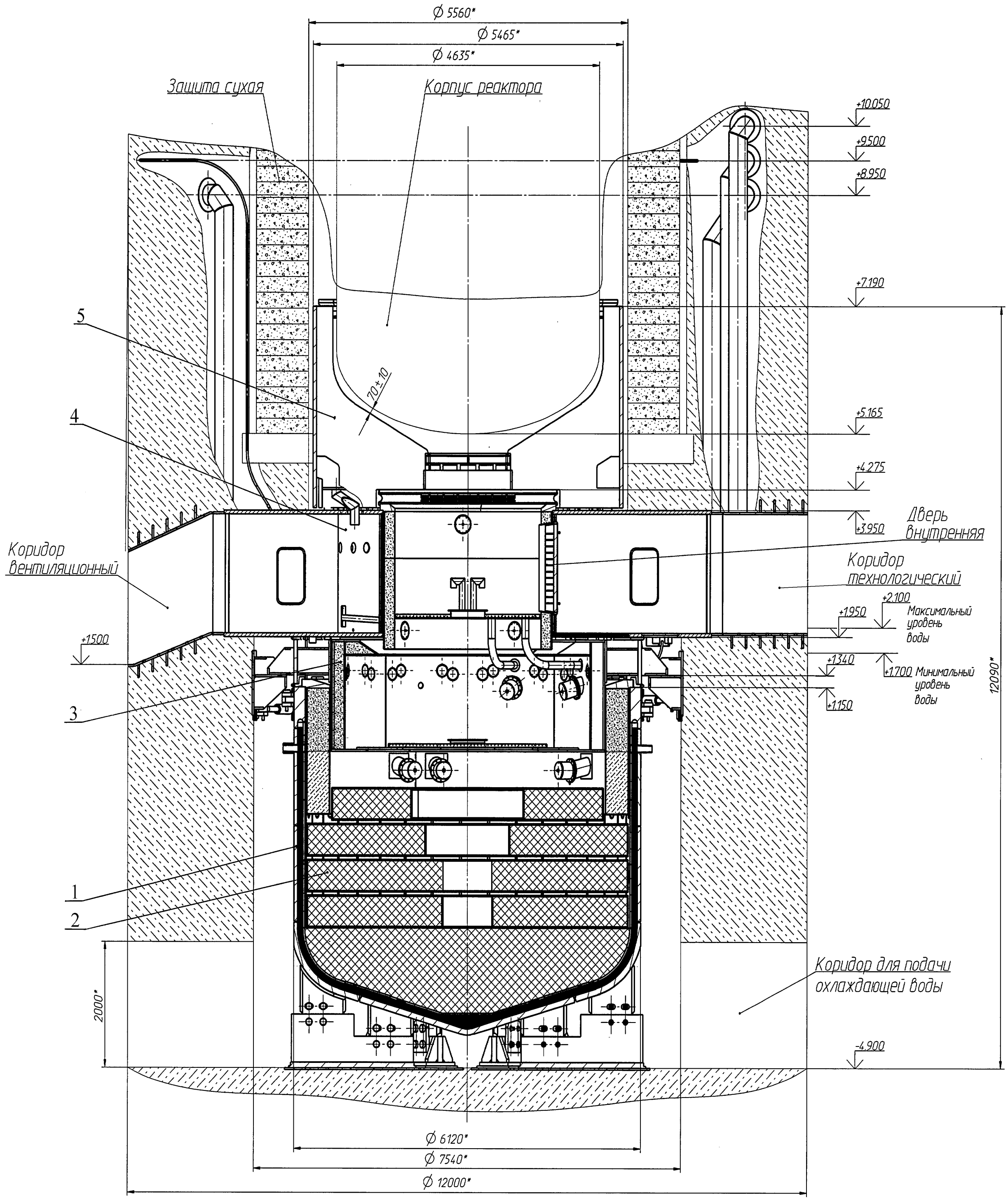
The ex-vessel melt retention aims to stabilize the corium outside the reactor vessel. In advanced reactor types the melt outside the vessel is retained in the core catcher. For operating reactors – where the core catchers were not part of the design – others methods are used to stabilize the corium outside the vessel depending on the cavity type. If the reactor cavity is normally dry, water is poured on the top of the melt from the failed reactor vessel, in the other case the cavity is already wet before the discharging of the melt.

1.3 Main functions of the core catcher

- Normal operation and not severe accidents:
  - air cooling of the dry protection;
  - biological shielding of the reactor cavity;

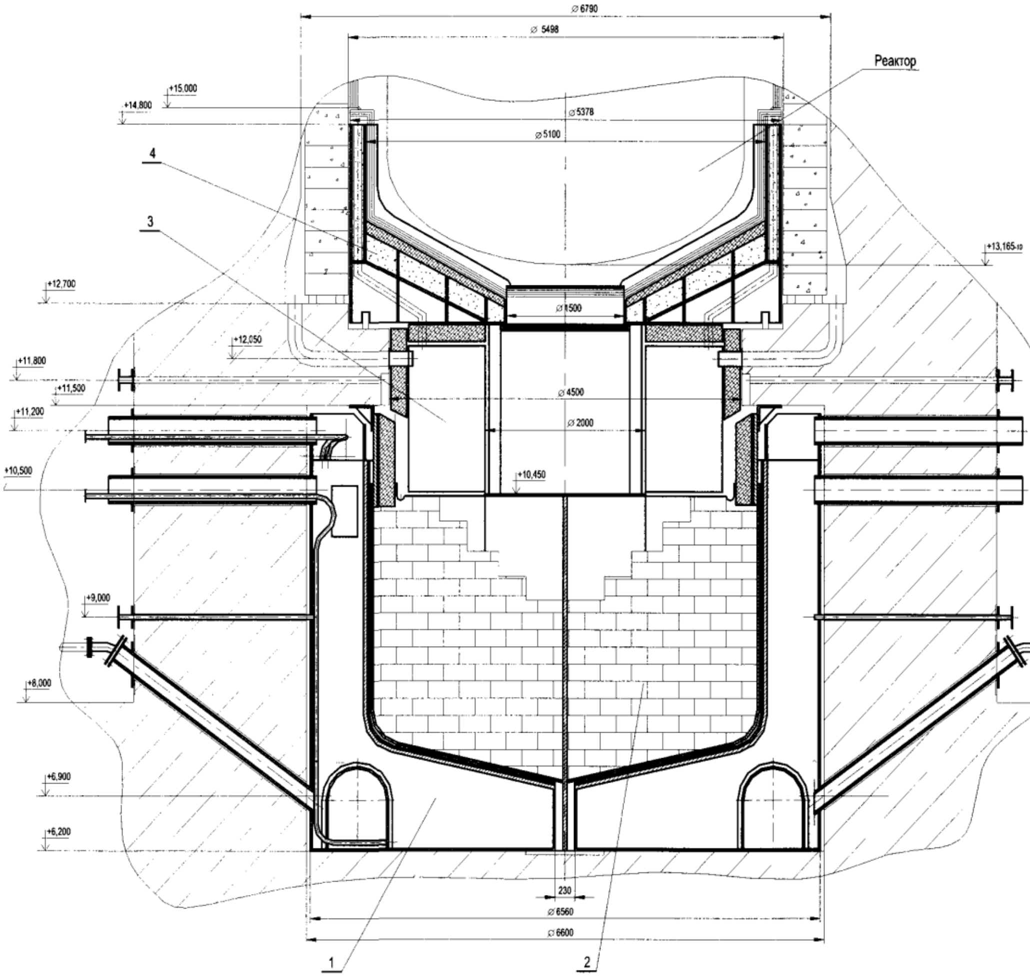
Reactor shaft recirculation cooling system is designed for cooling the reactor shaft, biological shielding, reactor heat insulation, "dry" protection, and the bottom plate during normal operating conditions.

The primary protection of the reactor shaft consists of a so-called "dry" protection and biological shield. The "dry" protection provides the radiation-and-thermal protection of the reactor shaft and it is made of concrete blocks. The biological shield reduces a level of irradiation from the reactor to the area of pipe connections and to the main joint of the reactor vessel. The biological shield elements represent steel boxes backfilled that reduces ionizing irradiation. The reactor shaft reinforced concrete walls service as the secondary protection.



AES-2006 Core Catcher

1. Core catcher vessel
2. Sacrificial material
3. Thermal shield
4. Cantilever truss
5. Reactor cavity



AES-91 Core catcher

1. Sectional heat exchange
2. Basket with filler
3. Vent duct
4. Bottom slab

- Severe accident:
  - reception and placement of the melt;
  - long term cooling of the melt;

After the melting-through of the reactor vessel, corium melt enters the space confined on the side and from below by the water-cooled steel walls of the core catcher, located in the sub-reactor space of the concrete cavity. Inside the core catcher is filled with sacrificial material, which consists of a special composition of steel and relatively light and low-melting oxides.

Corium melt entering the core catcher from the reactor interacts with the sacrificial material, which optimizes heat removal conditions, lessens the uncertainties resulting from the differences between various scenarios of severe accidents, and ensures inversion of metal and oxide components of the melt before water is supplied onto its surface.

Water supplying both on the surface of the corium and to the reactor cavity organized differently in AES-91 and AES-2006 design.

In AES-91, when the reactor pressure vessel is melted through and melt is released outside it, temperature increase in the beneath-reactor area indicates core melt release. When temperature in the beneath-reactor area reaches 1000°C, an alarm is activated on the BDBA panel informing personnel that core melt has started to release. Water is supplied for cooling molten corium surface in the core catcher upon expiration of 60 min after the moment of reactor pressure vessel destruction has been diagnosed.

In AES-2006, when the reactor pressure vessel is melted through and melt is released outside it into the core catcher, temperature starts to increase in the core catcher and the plugs in the water supply valves start to melt. In no earlier than 3 hours after the plugs melt completely, water is supplied to the surface. Operator can backup this action by supplying the water from the reactor inspection shaft.

In AES-91, water flowing by gravity from reactor internals inspection shaft, fuel pool and JNB tank is used for the core melt cooling. Excess water is discharged from the concrete cavity through the channels made in the upper part of the heat exchanger. Steam generated in the heat exchanger is removed into the containment space through the channels located above the heat exchanger. The cooling water inventory is sufficient for passive supply of cooling water into the core catcher for 24 hours in case of station blackout.

In AES-2006, water is supplied to the cavity during the loss of coolant accident. The reactor cavity is connected with the sump to both provide water to the cavity and to remove excess water from the cavity. Steam generated in the cavity is removed into the containment space.

- ensuring of the melt subcriticality;

Neutron and physical calculations have shown that while Gadolinium oxide (Gd_2O_3) in composition of sacrificial materials, the required sub-criticality ($K_{eff}<0.95$) is provided if unborated water is injected in the core catcher at any variants of structure (porosity within the whole space) and composition (ferrous and aluminum oxides) of corium.

- minimizing the release of radioactive materials;
- minimizing of hydrogen release;

After reactor pressure vessel has been destroyed, core melt is confined inside the core catcher. The core catcher ensures reception and confinement of core melt preventing interactions with concrete structures (reduces combustible gases emission), ensures passive residual heat removal from the core melt to the containment atmosphere, ensures mixing of molten core materials with sacrificial material in order to maintain sub-criticality and reduce hydrogen release. It can decrease the FP releases and ensures the thermal protection of the containment structures.

- prevention of ex-vessel steam explosions.

The core catcher design provides for special technical measures protecting inner space of the vessel from water ingress prior to core melt release from the reactor. This prevents the core melt from contact with water, when the core melt penetrates inside the core catcher interior.

Cooling water is supplied onto the core melt surface in the core catcher after release from the reactor pressure vessel, after melt inversion, on the oxide layer. As shown by experimental studies, in this case steam explosions do not occur.

2. Description of the System

2.1 Constructions of the core catcher and auxiliary systems (vessel, cantilever truss, thermal shield….)

Core catcher implemented in all new VVER designs are of “pot” type: its construction consists of a vessel, which is filled with sacrificial material. Vessel is passively cooled by water from the external surface of the vessel. There are two generations of core catcher design: 1st generation used in VVER-1000 units 1-4 of TNPP and 2nd generation used in AES-2006 power plants, both Leningrad and

Novovoronezh types of design. The designs of the core catcher in Leningrad and Novovoronezh units are mostly the same.

Main components of the core catcher are (see picture in p. 1.3):

- Vessel
- Bottom slab
- Cantilever truss (AES-2006 design only)
- Maintenance platform (AES-2006 design only)
- Sectional heat exchanges (AES-91 design only)
- Thermal shield
- Operator controlled water supply system (primary for TNPP, auxiliary for AES-2006)
- Passive water supply system (AES-2006 design only)

Bottom slab is used for directing corium to the core catcher vessel. Cantilever truss provides support for the bottom slab, I&C sensors and thermal protection, and is also used to supply water to the corium surface by operator and to release steam from the core catcher cavity. Thermal shield is used to protect upper part of the core catcher vessel form the thermal and chemical loads.

2.2 Selection of core catcher materials (constructions, sacrificial material, thermal shield)

The main core catcher construction material is steel. Thermal shield material is concrete with ferric and aluminum oxides.

The core catcher sacrificial materials have been chosen to fulfill the following requirements

- Low density of the oxide melt phase to ensure the inversion of melt
- Endothermic summary thermal effect from chemical reactions in the core catcher
- Zirconium oxidation without hydrogen release
- Subcriticality

According to these requirements and based on the various experiments, the sacrificial material is the mixture of ferric and aluminum oxides in 70/30 proportion plus binding material and gadolinium to ensure subcriticality. Due to properties of the sacrificial material, zirconium oxidation occurs with oxygen released from oxides, instead of steam oxidation, therefore, no hydrogen is released during the oxidation.

2.3 Measured parameters (normal operation, accident condition)

During normal operation, core catcher is in idle state. Temperature in the core catcher is measured to check if the core catcher is in normal operating conditions.

The main parameters to be monitored in severe accident conditions are temperatures inside the core catcher, inside the thermal shield, on some of the constructions (cantilever truss, maintenance platform), and water level in core catcher cavity. These parameters are monitored and used by operator to make decision to supply water to the core catcher cavity or to the melt surface.

2.4 Actuation logic (in different accident conditions)

Core catcher functioning is based on passive principle mostly. From the beginning of the severe accident ex-vessel stage the corium coming from the reactor vessel melts through the membrane in base plate and falls into the core catcher. After that the interaction between corium and sacrificial material starts.

The water is supplied to the core catcher cavity during the loss of coolant accident. Additionally operator as a backup action can supply water.

The water is supplied to the melt surface in the core catcher by the passive valves. The lock in the valve melts from the heat of the melt surface. Additionally operator can supply water from the reactor inspection shaft.

The actuation logic in AES-91 design differs from the AES-2006. Water is supplied by operator actions both to the core catcher cavity and on the melt surface.

2.5 Operator's actions (normal operation and accident condition)

During normal operation no operator actions besides the normal control of the parameters is performed.

During the sever accident operator controls the temperature inside the core catcher and water level in core catcher cavity. Operator actions in AES-2006 design are needed as supplemental only. When operator can determine that the corium release process is finished, he can supply water to the melt surface in the core catcher, this is only performed as a backup action in the case passive valve fault, the decision is made based on temperature of the thermal shield.

In AES-91, design operator should supply water both to the core catcher cavity and on the melt surface. This action is based on the symptoms of the ex-vessel stage of the severe accident.

Phenomenology of ex-vessel melt retention in the crucible type of the core catcher and experimental data supporting the design

2.6 Interaction of the corium and sacrificial materials

The interaction between molten corium and sacrificial material plays a key role in severe accident management utilizing a core catcher. The sacrificial material is designed to reduce the thermal loading on the core catcher structures in such a way that the core catcher maintains its integrity, which facilitates the cooling and retention of the core melt that has been released from the reactor pressure vessel. However, the sacrificial material alone is not adequate to reach this purpose, and the core catcher vessel must also be cooled from outside by a continuous circulation and boiling of water in a "cooling channel".

Various thermochemical, radiochemical and physical processes (such as inversion of the melt layers) take place in the core catcher between the molten corium and the sacrificial material (SM). In order to ensure adequate cooling, an overall endothermic effect must result from the different chemical reactions, and the physical processes (mixing of high power density melt with SM) must act towards reducing the thermal loading of the core catcher structures. In addition, re-criticality of the molten nuclear fuel has to be prevented to avoid any heat generation from fission reaction. The exclusion of the possibility of repeated criticality is achieved by the presence of a neutron absorber in the sacrificial material.

Most of the experiments for sacrificial material selection and optimization were performed at NITI with the RASPLAV test platforms, which facilitate testing with prototypic molten corium, and at the Kurchatov institute. A list of contributing research institutes and universities is provided in [1]. After experiments with different compositions of sacrificial materials, a composition that contains Fe_2O_3, Al_2O_3 and Gd_2O_3 as a neutron absorbing material was selected. Criteria for the sacrificial material selection are considered in [2]. The total amount of sacrificial material was determined based on the simulation results of various accident scenarios. The main reactions in the core catcher occur between the oxidic sacrificial material (OSM) and the oxidic corium. There are also smaller amounts of steel in the sacrificial material (SSM), mainly to be lessen the impact of molten steel released into the core catcher in the beginning of the melt release from the reactor pressure vessel. Basically, the core melt consists of two liquid components, oxidic and metallic, that have their own interaction patterns with the OSM and SSM.

Oxidic sacrificial material has several functions. When molten corium comes into contact with OSM, it starts to melt the OSM that consumes the amount of heat corresponding to the latent heat of fusion. The OSM dissolves into the high-temperature oxidic corium, and because the density of OSM is lighter than the oxidic corium, the overall density of the mixture decreases. As the lightest material in the core catcher, the mixture of OSM and oxidic melt forms the topmost layer of the melt pool. This “melt inversion” is described in more detail in Section 2.8. The metallic zirconium that has not oxidized in the in-vessel phase of the accident reacts with the iron oxide in the melt (zirconium is oxidized and the oxidic component reduced to metal), so that further hydrogen generation from steam-zirconium reaction is stopped.

2.7 Generation of the combustible gases

Hydrogen is generated by the high-temperature oxidation of the metals in the reactor core, main contributor being zirconium in the fuel cladding, and possibly other metallic structures of the plant that are significantly heated during the accident. Smaller amounts of other combustible gases such as carbon monoxide may be formed from melt interaction with certain materials (such as carbon steel). One function of the core catcher is to reduce the amount of oxidation of core materials with steam, and thus decrease the amount of combustible gases released into the containment atmosphere.

Reduction of oxidation is achieved by appropriate selection of the sacrificial materials. Metal unoxidized during the in-vessel stage of the severe accident will react with the oxides of the sacrificial material instead of steam. In this reaction, where steam is not present no hydrogen can be released. Thus, a part of the potential hydrogen generation during the accident is arrested by the core catcher. In addition, the relocation of the metallic part of the melt to the bottom prevents the direct contact of the oxidizable materials with the open atmosphere that has a high steam content above the melt pool.

2.8 Melt inversion

The inversion of metallic and oxidic layers of melt in the core catcher is expected to reduce the thermal loading on the wall of the core catcher, and to prevent focusing effect (high local heat flux caused by a thin metallic layer on top of an oxide layer) that could locally threaten the core catcher vessel integrity. The OSM has low density and high fusibility and it is easily dissolved by the oxidic corium, so that a homogenous oxidic mixture with a relatively low density is formed. Metallic uranium and zirconium are mixed with molten steel forming a mixture with higher density. Mainly due to the density difference, the oxidic and metallic layers in the molten pool are inversed. The light oxidic mixture forms the top layer of the melt pool, while the metallic layer travels to bottom of the core catcher. This process, called melt inversion, is expected to occur within a few hours of the arrival of the melt to the core catcher.

The SM-corium mixture should remain liquid until the end of the inversion to guarantee its effectiveness. Thus, one of the main objectives of the experiments for sacrificial material selection was to find out eutectic temperatures for the various SM compositions under consideration. The experimental database on melt inversion consists mostly of RASPLAV experiments [3].

The mixing of corium with sacrificial material increases the total volume of the molten pool. If the corium is effectively dissolved into the sacrificial material yielding a homogenous mixture, the volumetric heat generation rate and the heat flux directed at the core catcher wall become smaller. This reduces the risk of thermal mechanical failure of the wall by high temperature and results in an increased margin to the critical heat flux for the cooling of the vessel wall from outside (which is described in the next section).

2.9 External cooling of the core catcher

Regardless of the heat-absorbing properties of the sacrificial material, a large part of the decay heat generated by the corium is transferred though the wall of the core catcher to the surrounding medium. In order to make sure that the core catcher wall does not fail under the load, external cooling of the wall is required. For this purpose, the cavity that houses the core catcher is flooded with water, which evaporates in contact with the vessel wall. As the main heat transfer mechanism is boiling, a continuous water supply has to be arranged to the cavity. In order to ensure effective heat transfer from the core catcher wall, the heat flux caused by decay heat has to be lower than the maximum heat flux that can be transferred by nucleate boiling (the critical heat flux). At a higher heat flux, a steam film would be formed at the surface to be cooled, leading to deterioration of heat transfer.

The continuous steam flow generated in the core catcher cavity is directed into the upper parts of the containment, where the passive containment heat removal system (if the plant is equipped with it) condenses the steam to water to be re-used for cooling of the core catcher. An ultimate heat sink has to be provided to avoid eventual containment pressurization by steam. In VVER-1200 of Novovoronezh design, the atmosphere serves this purpose with the use of mobile cooling tower. VVER-1200 of Leningrad design has refillable external tanks outside the containment from which water evaporates to the atmosphere.

A large-scale thermal hydraulic model of the external cooling channel SPRUT has been set-up at Physics-Energy Institute in Russia. A range of heating power levels were examined using this facility [3]. Experiments showed effective heat transfer and steady boiling with no fluctuations at a power level exceeding the decay power by a factor of 1.8. Other thermal-hydraulic experiments investigated heat-transfer at curved or inclined surfaces, which are necessary to account for the curvature of the bottom part of the core catcher vessel. These test results were used to derive correlations for critical heat flux at inclined and vertical surfaces.

2.10 Water delivery on the melt surface

Delivery of water on the melt surface after all the melt has arrived to the core catcher is done for the purposes of (1) protecting the above structural components from the upwards-directed heat flux and (2) reducing the amount of radionuclides released from the melt. It is important to start the flooding only after all the melt has been released to the core catcher and the melt inversion has occurred in order to avoid the possibility of a steam explosion. The water delivery (flooding) may be done by passive melting plugs that open a flow path from the core catcher cavity to the core catcher interior at a certain temperature, or by operator action utilizing pipelines from a water tank to the core catcher (as described in previous Chapters).

In the long-term management of the accident, the melt pool is immersed in water and the boiling of the water layer on top of the pool stops, which is called water cooling mode. In order to achieve this, a continuous cooling circulation into the reactor core is established, possibilities for this includes e.g. restoring some of the emergency cooling systems that have not been operable during the accident. During the long-term cooling, the melt undergoes a slow solidification (crystallization) process, first (in short-term) by forming a crust on top of the molten pool, and next by solidification from the walls and bottom towards the center of the melt. In total, the solidification takes several months. The solidified form of the corium is stable and the fission products release from the solid is much less compared to earlier stages of the accident. During this time, the core catcher structures are subject to corrosion, the depth of which has been evaluated to be small [1].

The phenomena associated with water supply to metallic and oxidic melt have been studied in ETU-M1/M2 and RASPLAV-2 experiments, respectively [3]. Steam explosions were not observed in the experiments. Oxidation rates, oxygen release rates and emissivity of the melt surface were also studied in these experiments.

2.11 Release of gases during interactions in the core catcher

One of the issues that has been taken into account in the selection of the chemical composition of SM is the possibility of gas formation when the core melt comes into contact with the SM. Gas formation (phase separation of the melt) should be minimized because it can cause many adverse effects including increased pressure by non-condensable gases, release of radioactive compounds and release of hydrogen and other undesired chemically active substances. This goal limits the number of materials that can be used in the core catcher because not many materials are able to withstand the melt pour without gas formation and interact with the melt in the required manner.

During the initial interaction of core melt with SM the decomposition of iron oxide is a potential source of oxygen, which can contribute to the risk of combustion and increases the amount of non-condensable gases in the containment. On the other hand, the generated oxygen may be consumed in the on-going oxidation reactions with the metallic melt that enters the core catcher and, as a consequence, is retained in the melt pool.

The experiments performed with the RASPLAV facility suggest that there are no oxygen releases from the interactions between OSM and fully oxidized corium, and virtually no gas releases from interaction between metallic melt and OSM at high temperatures [3]. Some hydrogen is released in the interactions between water and the steel melt, and water and zirconium as reported in ETU-M1/M2 experiments, which investigated top flooding of the melt [3].

2.12 Fission products (aerosols) release

An important function of the core catcher is to reduce the amount of radioactive materials released into the containment. Aerosol-form fission products not retained in water pools or surfaces of the primary circuit or containment cause an increase to environmental releases in case of loss of containment leak-tightness. In general, an effective way to reduce the release of airborne fission products in the ex-vessel stage of the accident is to minimize the contact between the melt pool and containment atmosphere.

Aerosol releases from the core catcher have been studied in experimental programs applying a fission product simulant material. The RASPLAV experimental results suggest that aerosol releases from interactions between fully oxidized corium and OSM are very low [3]. According to these experiments, over 96% of the aerosol release is uranium oxide. RASPLAV-2 experiments suggest that the water pool on top of the melt binds most of the aerosols. This is expected to be achieved at latest when steady-state cooling (water cooling mode) for the core catcher has been reached. In RASPLAV-2 experiments, a part of the aerosols was absorbed into the steam film and into the steam bubbles escaping through the water layer, but the aerosol concentration of the outgoing steam was reduced compared to release from the open melt surface [3].

3. Governing scenario

As the basic scenario of a severe accident, to justify the efficiency and robustness of the core catcher, the LBLOCA scenario, accompanied by a long blackout is accepted. In this scenario, the rate of accident progression is maximal. Time from the beginning of the accident to the moment of the melt release from the reactor vessel is about 6000 s. This is the scenario with the maximum decay heat release to the core catcher.

For this scenario, it is necessary to confirm that reliable heat removal from the melt in the core catcher to the water cooling the external wall of the vessel is ensured and to demonstrate significant departure from the critical value of the heat flux on the external surface of the vessel. Since the thermohydraulic analysis of the melt behavior is still characterized by a high uncertainty, the margin to the critical heat flux should be order of 2.

In addition, it should be demonstrated that a passive valve designed to supply cooling water to the surface of the melt in the core catcher will be melted and will provide water to the surface of the melt timely, not earlier than the inversion of the melt occurs, and oxides more light than the metallic fractions of the melt will collected on the surface. The safe water supply to the surface of the oxides was confirmed by appropriate experiments [3].

In addition, for the base scenario, it should be demonstrated that the thermal protections perform their functions and protect the structures from the heat flux until water will be supplied to the melt surface. In addition, it should be confirmed that the spread of the melt inside the core catcher will not lead to the melt through the outer wall of the vessel, that is, the integrity of the core catcher vessel will be preserved.

In addition to the above, it should be demonstrated that heat removal from the outer surface of the core catcher and from the melt surface leads to limited growth and a subsequent stable decrease of the melt temperature.

Since the design of the core catcher establishes a limitation on the pressure drop under which the melt must exit into the core catcher vessel ($\Delta P < 1$ MPa), the most unfavorable scenario should be analyzed relative to the fulfillment of this condition. As a rule, a scenario of prolonged complete blackout with total loss of secondary side heat removal is selected, for which it should be shown that the available means of reducing pressure can reduce the pressure in the primary circuit before the reactor vessel will be destroyed.

However, in some of the countries (Finland, Hungary, and China), regulations require that the possibility of failure of the reactor pressure vessel under high-pressure is excluded by implementing a reliable system for primary circuit pressure reduction at the start of a core melt accident. In this case, this scenario is usually not important as a limiting case for core catcher design.

It is advisable to consider the spectrum of leaks with a smaller diameter MBLOCA and SB LOCA, since the magnitude of the leak determines the rate of development of a severe accident and affects the duration of some phases of the in-vessel stage of the accident. This, in turn, affects the oxidation state of the metal phase, which enters the core catcher as part of the melt, and, accordingly, can affect the amount of hydrogen that is generated during the ex-vessel phase of a severe accident.

The leak flow rate also affects the rate of melt release from the reactor vessel, and accordingly the rate of heating of the passive valve. Since the supply of water to the surface of the melt should start at least after the completion of the melt release, it is advisable to analyze the widest possible range of leaks in order to determine the possible range of the duration of the melt release.

4. Final safe state of the core catcher after severe accident

The state of a core catcher following severe accident could be accepted as a final safe state when the following conditions are provided:

a) the core debris is solidified and its temperature is stable or decreasing,
b) the heat from the core debris can be transferred into an external heat sink,
c) the configuration of the core debris is well below criticality,
d) the release of radioactive products from the core catcher into the containment is practically ended.

5. References

[1] Khabensky et al. Severe Accident Management Concept of the VVER-1000 and the Justification of Corium Retention in a Crucible-Type Core Catcher. Nuclear Engineering and Technology 41, No. 5, June 2009.

[2] V. V. Gusarov et al. Physicochemical Modeling and Analysis of the Interaction between a Core Melt of the Nuclear Reactor and a Sacrificial Material. Glass Physics and Chemistry, Vol. 31, No. 1, 2005, pp. 53–66.

[3] Design bases of the core catcher for AES-2006 and TNPS 1-4. Presentation by Rosatom. 9th Meeting of the MDEP VVER SA TESG, Moscow, September 26-27, 2018.