CRUCIBLE TYPE CORE CATCHER FOR NPP WITH VVER-1000 REACTOR

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ABSTRACT

This paper deals with the design and justification of a crucible-type core catcher for NPP with the VVER-1000 reactor. Major functions as well as design bases are considered, including the data for melt release from the reactor pressure vessel. The main information of the design justification is discussed and results are presented.

1. INTRODUCTION

The core catcher is intended for reception; suppression and cool-down core melt materials in course of severe accidents associated with core degradation and reactor pressure vessel failure. Radiation consequences of severe accidents decreased to the safe level by using the core catcher.

The core catcher performs the following main functions:

- Receives and retains within its volume liquid and solid corium components, core and reactor structural materials debris;
- Provides stable heat transfer from corium to cooling water and reliable corium cooldown;
- Ensures corium subcriticality in the concrete cavity during its cooldown;
- Ensures minimum release of radioactive materials and hydrogen into containment space;
- Keeps in place bottom head of the reactor pressure vessel when is containing core debris. Core catcher keeps bottom head in case of its deformation and rupture until corium ejected to the concrete cavity;
- Protects elements of the concrete cavity and prevents them from thermomechanical effects of moving corium.

This paper presents the accepted concept of the core catcher for typical VVER -1000 reactors, its design features, and also justification of the accepted technical solutions.

2. CONCEPT OF THE CORE CATCHER

The concepts of core melt localization and cooling has been recognized as an efficient accident management measure for light water reactors (LWR) to mitigate the threats to containment integrity after core melt pouring in the concrete cavity. From different possible solutions the major attention was given to following concepts.

The first concept is based on the retention of the core melt within the reactor pressure vessel during passive cooling of the outside surface of the vessel by maintaining nucleate boiling of the cooling water. This concept was justified and implemented for medium power NPP including NPP with VVER-440 reactor, Loviisa, Finland [1], in the AP-600 design [2] and NPP with VVER-640

[3]. Now the possibility for application of the in-vessel melt retention concept is considered for all existing units with VVER-440 reactors during their backfitting.

The second concept of core melt localization which is developing now includes ex-vessel device where corium spreads along a large horizontal surface in a special compartment where a subsequent passive steam-water cooling is provided.

Corium moving from the reactor pressure vessel to the localization compartment is organized in two stages. During first stage corium moves to the special storage (pre-catcher) where its interaction with specially selected sacrificial material changes melt parameters to ensure its further horizontal spreading in the localization compartment. The pre-catcher where corium is retained for about one hour, is designed to smooth friction regardless of accident scenarios, and also oxidize free zirconium containing in the core melt. In the second stage, corium moves through the sloped channel to the next suppression compartment. The spreading area should be large enough to ensure appropriate thickness of the corium layer on the horizontal surface. The Curium cooling is performed by passive water supply only onto its surface, or in a combined way, with cooling from below and surface at real-time, as it was proposed for the COMET concept (Alsmeyer H., 1999) [8].

While choosing the core catcher concept for NPP with VVER-1000 the concepts mentioned above were analyzed. The following factors were also taken into account:

- experience on justification the IVR concept for VVER-640 design;
- availability of free volume in under-reactor concrete cavity in VVER-1000 design;
- availability of large water inventory inside a containment (in the reactor safety and auxiliary systems and spent fuel pool) which can be driven to the core melt localization area by gravity and be used for cooling down of corium;
- insufficient spreading area in the VVER-1000 containment compartments adjoining the under-reactor concrete cavity so the concept accepted in the EPR design can not be used.

Taking into account above mentioned factors, the crucible type core catcher concept was accepted for VVER-1000 which combines elements of in-vessel core melt retention (passive water cooling of special steel vessel which is installed under reactor) and elements to keep physical and chemical properties the corium consist and stable (application of sacrificial material).

3. INPUT DATA FOR CORE CATCHER DESIGN

Development the core catcher design requires input data on the scenario of core melt relocation such as timing of events and masses of core components which determine the interactions with the sacrificial material. These data were obtained by the analysis of melt progression in case of in-vessel stage of a severe accident. In modern practice the best estimate computer codes (realistic codes) are typically used for severe accidents analysis. There are several such codes in the world, the most known of them are RELAP/SCDAP and MELCOR codes. The Russian code RATEG/SVECHA/HEFEST was used for analysis of series of beyond design basis accidents. According to PSA-1 results while designing a core catcher the accidents with core damage probability higher than 10^{-7} were selected.

The list of accident sequences analyzed for specifications of initial parameters while developing the VVER-1000 core catcher, includes such accidents as small and large breaks LOCA from the primary coolant circuit with nominal diameter ranged from 25 mm to 346 mm with superimposition of an extra failure like a complete station blackout (SBO) or failure of ECCS active part, and also SBO scenarios with intact primary circuit. Let's note that the results of these calculation analyses were also applied for justification of hydrogen safety for NPP with VVER-1000, analysis of long-term containment loading processes and development of the recommendations for severe accident management. The accident with a main circulating pipeline break (D_{nom}850 mm) and superimposition of an extra failure was not considered since according to PSA results the probability of such beyond design basis accident is lower than 10^{-7}. Input data include mass and temperature of steel and oxide melts moving to the core catcher, zirconium oxidation degree, time of melt movement, and decay heat. It was shown that for all considered accidents the core melt relocates to the core catcher in two portions: the first gross ejection (during about 30-60 sec), and second portion of corium relocating approximately during subsequent 1800 sec. Amount of oxides, steel and zirconium in the melt composition, time of its moving are scenario-specific, however, masses of oxide and metal components of the core melt do not exceed 105 and 120 tons, with their temperatures 2600 and 2000°C, accordingly. The example of RATEG/SVECHA/HEFEST calculations is shown in Fig. 1 where corium components release to the core catcher is presented for the severe accident with a break of equivalent diameter of 346 mm (pressurizer surge pipeline) and superimposition of SBO.

4. DESIGN OF CRUCIBLE CORE CATCHER FOR VVER-1000

On the basis of the accepted concept and obtained input data the core catcher design presented in Fig. 2, Fig. 3 and Fig. 4 had been developed. The device includes the following basic elements:

a) lower plate; b) sectional heat exchanger; c) basket filled with a sacrificial material;

The lower plate is intended to receive corium ejected from the reactor pressure vessel, to direct it into a basket, and also to support the reactor pressure vessel bottom head during its deformations. To ensure reliable corium flow, the upper surface of the lower plate is covered with a special fast-melt concrete layer playing role of “lubricous layer” for corium.

During severe accident after reactor pressure vessel melt-through the molten corium moves to the core catcher through the central hole in the lower plate and interacts with the sacrificial material which is located in the basket. Heat is transferred from the melt by circulating cooling water behind a heat exchanger wall (see Fig. 2). The sectional heat exchanger has 12 sections. All heat exchange sections are interconnected by an arch header. The sectional heat exchanger completely protects the lower and side surface of concrete cavity from heat flux caused by corium. The water is supplied in a sectional heat exchanger and onto the melt surface from the reactor water inventory in auxiliary systems and spent fuel pool with the help of specially designed system which is presented in Fig. 5. The water is supplied to the core catcher after opening the automated gate valves (5), (6) and (7) which are installed redundantly at the pipelines. Water inventory in safety and auxiliary systems and spent fuel pool is enough to ensure melt cooling during 24 hours after onset of core degradation. After one day from the moment of accident initiation, power supply is to be restored and the recirculation of water from the sump to be provided.

The key feature of the new core catcher is sacrificial material: specially selected composition on a basis of Fe_2O_3, Al_2O_3 and sacrificial steel. Oxide sacrificial material is made as ceramic triangular bricks are assembled in hexagonal steel cartridges. The cartridges are located in the core catcher basket. The mass ratio for light oxides of iron and aluminum in the ceramic bricks is 70% of Fe_2O_3 to 30% of Al_2O_3. To maintain sub-criticality of the melt for all possible ranges of temperature and water-uranium ratios, gadolinium oxide is added to the oxidic sacrificial material.

Sacrificial material provides the following functions:

- reduction of core melt temperature due to integral endothermic effect during interaction of sacrificial material with the corium;
- increasing the volume of melt thus providing larger heat transfer surface between corium and cooling water in the heat exchanger, reduction of heat flux at the walls and increase of the CHF margin;
- inversion of the oxide and steel layers in the melt pool;
- decrease of the corium chemical activity due to oxidation of its components by sacrificial oxides;
- minimize the production of hydrogen in course of metal zirconium oxidation. Zirconium oxidation accurse during corium interaction with ceramic sacrificial material;
- ensuring core melt subcriticality.

After interaction of oxide corium with sacrificial material, density of the formed oxide melt mixture becomes less than the melt steel density, and melt layers are inverted. Melted metal moves to the lower part of the basket and the oxide mixture floats upwards. Upper location of oxide layer of the melt reduces thermal loading to the heat exchanger walls. After inversion water can be supplied onto the oxide melt surface without danger of steam explosions and hydrogen generation from steam-metal reactions.

The severe accident management scheme using for core catcher design is carried out according to the following algorithm:

- During normal operation, design and beyond design basis accidents without core damage, heat exchanger and basket with a filling compound are drained, the basket is hermetically closed.
- After signal alert that shows temperature above the core exceeds 400°C and indicates possible transition of a beyond design basis accident to the severe accident stage, the operator opens the valve (5) at the connecting line of the auxiliary water inventory with the heat exchanger to initially fill it with water (see Fig. 5). In this period the core catcher is in the stand-by mode.
- After moving the first portion of the melt to the basket which is detected by thermocouples installed in the upper part of the basket, the operator opens the valve (6) and passive stationary make-up of the multi-sectional heat exchanger begins by cooling water.
- Interaction of corium with sacrificial material. Inversion of the melt layers.
- Delivery of water onto the melt surface by opening a valve (7) installed at the line from the fuel pool to the core catcher after the specified period of time is sufficient for melt inversion.
- Passive steady heat transfer from the melt to the cooling water; water boils in the sectional heat exchanger, steam is discharged via the steam channels to the containment volume.
- Recirculation of sump water along with its cleaning and cooling is provided after power supply recovery. Also water inventory in fuel pool is replenished.
- At the melt cooling and subsequent crystallization stage the steady decrease of corium temperature is provided. According to the estimations carried out, complete bulk corium

crystallization occurs approximately after 1 year from the moment of relocation to the core catcher.

It can be underlined that the core catcher operation is mainly based on passive principles. The only active devices are automated valves which are installed at the pipelines connecting the water inventory in auxiliary systems and the fuel pool with the core catcher's heat exchanger. Their power supply is organized from the special (extra) channel of power supply, stipulated in the new NPPs with VVER-1000 design, specially for severe accidents management. Power supply to instrumentation of measuring the parameters of main core catcher equipment, is performed from the same channel.

5. CORE CATCHER JUSTIFICATION

Importance of the core catcher in the general safety concept for NPP with VVER-1000, novelty of many accepted solutions, and also the fact, that the device of similar type is created for the first time in the world practice have led to strict requirements to justification of the accepted solutions. All activities aiming at core catcher justification can be generally divided into the following basic directions:

- experimental investigation of local heat transfer processes;
- developments of computer model that describing core catcher operation;
- justification of separate core catcher elements;
- development and investigation of new materials.

Investigation of heat transfer crisis at the sloped surface of the heat exchanger have shown that the heat fluxes from corium are less than critical values more than 2 times for heat flux removal from the outer surface for the most conservative scenarios of severe accidents.

The thermal hydraulics investigation was carried out for one section of the heat exchanger at the experimental facility with 1:1 vertical and horizontal scale factors and 1:3 azimuthal scale factor related to the real heat exchanger section. The heat transfer reliability has been confirmed for thermal loads relevant to the real ones; the accepted technical solutions for heat exchanger design have been proved. Experiments on water supply onto the melt surface have confirmed that water supply is reasonable after melt layers inversion; there is no steam explosion during interaction of water with uranium-containing oxide melt. Investigation of oxide and steel melts interactions with sacrificial material allowed to develop the relevant calculation models. The sub-criticality investigation has shown that addition of gadolinium dioxide to the sacrificial material composition allows eliminating completely the possibility of re-criticality during all stages of melt cooling. Thus, the accepted technical solutions for sacrificial material composition and location in the core catcher have been proved from the point of view of formation the secondary critical masses.

6. CONCLUSIONS

There are several concepts for core melt localization within the containment during severe accident. After analyzing different concepts for localizing curium it was justified that crucible type core catcher is optimum variant for VVER -1000 reactors. Justification of the core catcher design has been carried out by calculation. The major characteristic parameters of corium were obtained on the basis of calculations. Using the new sacrificial material compositions ensures core melt sub-criticality and allows eliminating completely the possibility of re-criticality during all stages of melt cooling.

The core catcher of this type can be recommended for the designs a NPP with new generation VVER.

NOMENCLATURE

CBO	complete station blackout	IVR	in-vessel retention
CHF	critical heat flux	LOCA	lose of coolant accident
COMET	corium melt ex-vessel transport	PSA	Probabilistic Safety Assessment
EPR	European Pressurized Reactor	SNL	Sandia National Laboratory
ECCS	emergency core cooling system		

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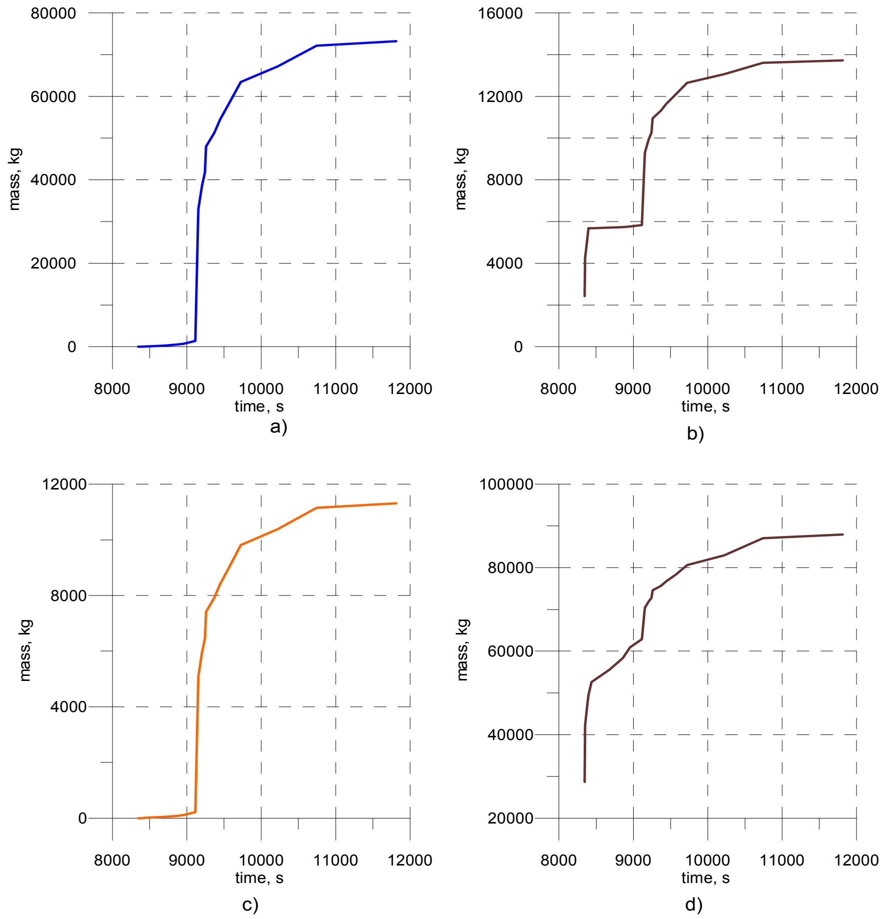
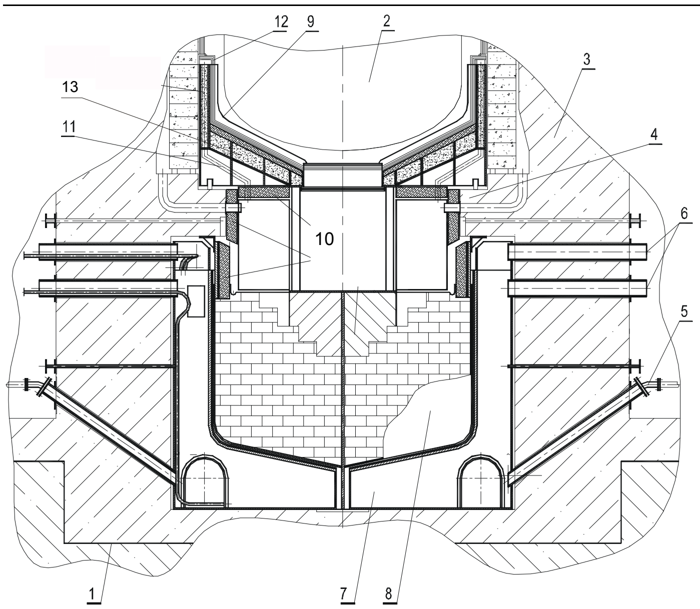


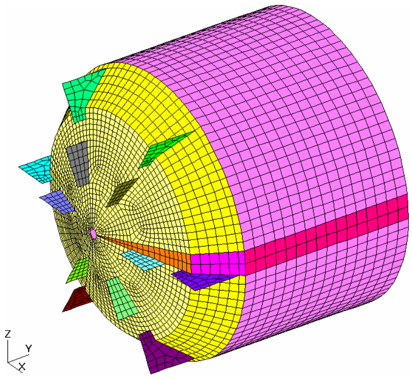
Fig. 1 Example for calculation of corium components release to core catcher

(LB LOCA D_{nom} 346 mm with SBO) a) UO_2 b) Zr c) ZrO_2 d) steel



1 – Containment
2 – Reactor
3 - Concrete cavity
4 - Concrete cantilever
5 - Device for coolant supply
6 - Device for coolant removal
7 - Ring sectional heat exchanger
8 – Basket
9 – Protective truss
10 - Heat insulation panels
11 - Air cooling channels
12 - Heat insulation
13 –Lower plate

Fig. 2 Design of VVER-1000 Core Catcher



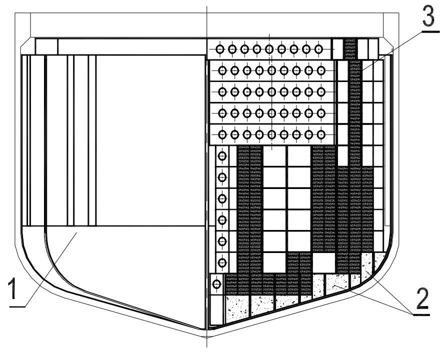


Fig. 3: Over view of core catcher 1. basket 2. fundament 3.sacrificial material

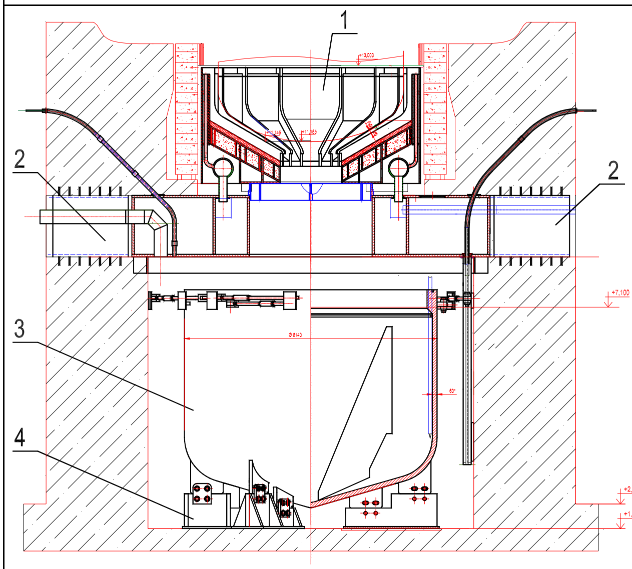


Fig. 4: Core catcher layout in reactor pit

1- Lower plenum of RPV 2- Embedded supporting ring

3-Basket 4-Fundament

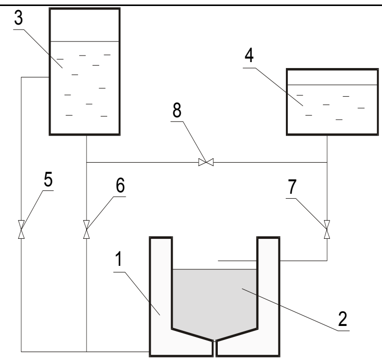


Fig. 5: System of water supply for core catcher cooling down.
1– Heat exchanger
2 – Melt of corium and sacrificial material
3 – Water inventory in auxiliary systems
4 – Fuel pool
5,6,7,8 – Gate valves