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THE METHOD OF CORIUM COOLING IN A CORE CATCHER OF A LIGHT-WATER NUCLEAR REACTOR

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During the development of a severe accident at nuclear power plant with a core melting, corium is formed. One of the main barriers preventing outflow of corium into the environment is a melt localization device or a melt trap. The melt trap must accept and prevent the corium parameters from exceeding critical values, ensuring its retention in a controlled volume and cooling. For this reason, melt traps are subject to serious requirements regarding cooling methods to ensure effective containment of the melt in the core of a nuclear reactor. In the presented article, experimental studies of the interaction between corium and water, which was supplied to the surface of the corium in a melt trap for its cooling, were analyzed. As a result of the work, a number of significant problems associated with the low efficiency of this cooling method were identified, and possible ways to eliminate them were considered. A solution is proposed for optimizing the method of corium cooling in a melt trap, as well as for the scope of research on the possibility of implementing the proposed method in practice and analyzing its effectiveness using the VCG-135 test-bench and the Lava-B facility.

Keywords: corium, severe accident, core catcher, VCG-135 test-bench, Lava-B facility, safety, hydrogen generation, steam exposure.

Introduction

One of the main directions of research in the field of operation of nuclear power plants is the issues of its safety, in particular, the localization and cooling of the melt from the structural materials of the core (corium) during the development of a severe accident with loss of coolant. At the same time, this process is carried out in the so-called melt localization device (MLD) of the core, located under the power vessel of the reactor. The main task of the melt localization device is to accept and cool the corium in the localization volumes as quickly as possible in order to prevent its heating, outflow of non-volatile fission products and prevent the formation of re-criticality [1].

To date, there are several options of the under-reactor melt trap [2], among which the most well-known are the so-called “crucible” options of the melt trap for trapping molten materials from the core. These traps are already used at existing nuclear power plants, such as the Taiwan NPP in China, and at power units currently under construction with the latest Russian-made water-water energetic reactor (WWER) [3].

Corium is a mixture of two components that are immiscible with each other: metal and oxide. The metal component of the corium is formed as a result of the melting of steel internals and the wall of a nuclear reactor, and the oxide component is formed as a result of the melting of pellets with nuclear fuel and the dissolution of metal zirconium and zirconium oxide in this melt, formed as a result of oxidation of metal zirconium by water vapor and atmospheric oxygen. The density of the metal part of the corium is less than that of the oxide part, which causes stratification of these melts in the joint presence [4].

To cool the corium and prevent it from leaving the trap, the concept of cooling the corium in a crucible trap was developed. The concept is based on filling the under-reactor space with blocks of cassettes filled with sacrificial material. The sacrificial materials, interacting with the corium, change its properties, thereby creating conditions for the reliable operation of the MLD. The role of sacrificial materials is to dilute the heat-producing oxide part of the corium in order to create conditions for the gravitational inversion of parts of the corium and reduce its high temperature [5]. The melt formed in the trap is cooled by heat removal to the cooling water through the shell, as well as by water supplied directly to the melt surface. The described system is operable, however, in the course of further research, it was found that the corium-water interaction has serious negative phenomena: the formation of explosive hydrogen during steam-metal reactions and the threat of steam explosions as a result of a batch outflow of corium from the reactor pressure vessel [6].

Obviously, in order to prevent negative consequences during the development of a severe accident at a nuclear power plant, it is necessary to conduct experimental studies on the interaction of corium with cooling water in order to better understand the ongoing processes. For example, such experiments are in demand in studies that have been and are being carried out as part of the development of the concept and the creation of severe accident control systems by cooling down, controlled movement and localization of the core melt outside.

The purpose of this article is to review previous experimental studies of the interaction between corium and cooling water. As a result of the work, problems were identified that arise when water is directly supplied to the melt pool, an analysis of existing methods for eliminating the identified problems was made, and an optimization solution was proposed to minimize these disadvantages.

1. Interaction of water with corium

A feature of the localization of the core melt in the melt trap is the portioned outflow of the corium from the reactor pressure vessel. In this case, water for cooling the corium is supplied immediately after the first portion of the corium enters the trap. This leads to the fact that at outflowing of the second portion of the corium (approximately 0.5 - 1 hour after the outflow of the first portion), a water pool is formed on the surface of the melt. In this case, when a high-energy melt falls into a container filled with water, there is a possibility of a steam explosion, as a result of which not only the device for trapping the molten materials of the core, but also the concrete burden with a sealed zone can be destroyed [7].

The first major studies on the conditions for the occurrence of steam explosions during severe accidents at nuclear power plants were conducted at the Sandiev Laboratories (USA) in the well-known series of FITS experiments. As a result of research, steam explosions occurred with water volumes from 44 l to 0.25 m^3 with a melt mass of 3 to 20 kg. At the same time, the contact of some melts with the coolant did not lead to an explosion, and a clear effect of the composition of the melt on the explosion hazard is also traced. With an open geometry, in most experiments with Al_2O_3-Fe, a spontaneous explosion was observed ($\eta\infty$ from 0.2% to 3% of the total thermal energy of the melt), while no explosions were observed when using an A + R corium mixture [8]. Similar experiments conducted at the Premix test-bench in Karlsruhe showed that the fall of, for example, only 20 kg of melt into a 0.5 m3 container with water leads to steam explosions with a pressure increase above 2 MPa, which ultimately destroyed the installation [9].

However, the opposite pattern was observed as a result of nine experiments conducted in a series of WUMT experiments, where a 24 kg melt was poured by gravity through a washer into a tank of water. In this series of experiments, a steam explosion took place in only two out of nine experiments. In experiment 03, the explosion occurred before the melt reached the base of the vessel. In this case, the subcooling of the water was 80 K, and this large subcooling can be considered responsible for the spontaneous initiation of the explosion that took place. In experiment 09, an explosion occurred in water that was on the saturation line 0.5 seconds after the melt reached the base of the vessel [10].

In a similar series of HPTR experiments, in which 5 kg of the melt was poured into a water volume (1 l) located in a pressure vessel, the only initiator of a steam explosion that had an effect was a large flow of water. In experiment 05, it initiated a steam explosion, and in experiments 13 and 14, it led to enhanced vaporization. The steam explosion in experiment 05 took place at a pressure in the vessel of 5.8 MPa (the pressure increase before the explosion was caused by the mixing of water and melt in a closed volume) [11]. Typical out-of-vessel steam explosion conditions occurring during a severe accident were simulated in the COTELS project experiments (Series A). In all these experiments, there was no pressure surge typical for a steam explosion. The largest pressure peak was recorded in the A8 experiment, where the corium fell at the highest rate [12].

During the experimental studies on the interaction of water with melts, additional features were noticed. Thus, as a result of the FARO experiments, information was obtained that a significant amount of hydrogen is produced during the corium-water interaction. Since the composition of the melt in this case was the same as in the KROTOS experiments, it is likely that hydrogen was also formed in them. Although during the described KROTOS experiments there were no devices for detecting the appearance of hydrogen during mixing of water and melt, its presence can be concluded from calculations based on the results of the KROTOS 41 and KROTOS 45 experiments using the COMET code [13–14].

These results have led to the emergence among specialists of scenarios of a hydrogen explosion during the supply of water to the corium. There is evidence that corium is a system of two immiscible liquid phases—oxide and metal. Due to the difference in densities of the two systems, the metal part of the corium is located above the oxide one, that is, water is directly supplied to this system of the corium to cool it.

Experiments on the interaction of water with steel melts have shown that even at temperatures above 1300 K, intense interaction of metals with water and steam occurs with the formation of hydrogen. Experimental studies have confirmed the importance of the processes of hydrogen formation during high-temperature oxidation with water and water vapor of steel melt as an additional source of hydrogen, which should be taken into account in hydrogen safety [15].

In this regard, it can be assumed that with the active interaction of water with the metal part of the corium, there is a possibility of the formation of a critical concentration of hydrogen, which can lead to its detonation, which, in turn, means that the conditions for hydrogen safety cannot be met, which means, containment integrity cannot be met as well. An additional problem of interaction with water of the metal part of the corium (especially zirconium) is the release of a large amount of heat caused by chemical reactions, as well as the combustion of the resulting hydrogen and oxygen [16].

Thus, as a result of the analysis of previous studies of the interaction between corium melt and water, the following conclusions can be drawn:

- In major part of experiments, steam explosions have not been observed, but nevertheless, under certain conditions, it occurs. This means that when corium falls into the water pool in the melt trap, the probability of a steam explosion is not zero, so further work should be done to prevent steam explosions that threaten the integrity of the melt receiving device;
- During experiments to study steam explosions, it was found that during the corium-water interaction, a significant amount of hydrogen is generated. At the same time, in many experiments there were no sensors for detecting hydrogen, however, the fact of the presence of hydrogen in the gaseous medium is confirmed by subsequent experiments and the created calculation codes.

2. Fundamental solution to the identified problems

Minimizing the formation of hydrogen and reducing the threat of a steam explosion in a crucible-type melt trap is expected by applying the concept of gravitational inversion of parts of the corium. Sacrificial materials are the central object in the implementation of this concept. Sacrificial materials are used to dilute the heat-generating oxide part of the corium in order to create conditions for the gravitational inversion of parts of the corium and reduce its high temperature.

In crucible devices for localizing the melt, it is assumed that, being melted when heated from the melt, sacrificial materials form a composition with the uranium-containing oxide part of the fuel melt, the specific density is lower compared to the metal part of the corium, which, in turn, will allow the oxide phase to float to the top part of the trap. When liquid oxides enter the surface, the cooling water does not create a threat of steam explosions, which is associated with the thermophysical features of liquid oxides, and does not enter into chemical reactions with them to form hydrogen, does not undergo thermal decomposition due to the relatively low temperature of the melt mirror [17].

To substantiate the possibility of implementing this concept, a series of experiments was carried out to study the interaction of candidate sacrificial materials and corium in a crucible-type melt trap within the framework of numerous series of experiments, among which Melt, Vesta, CORMIT [18–20]. As a result of experimental studies of the interaction of candidate sacrificial materials with corium, it was found that ceramic materials are the most optimal sacrificial materials. For example, ceramics based on hematite and alumina were chosen as the sacrificial material for the melt trap of the WWER-1000 reactor. The experiments showed that the mutual dissolution of the sacrificial material and the melt occurs at a rate sufficient to implement the inversion of the oxide and metal layers in <1 h [21]. Thus, the possibility of implementing the concept of gravitational inversion was experimentally confirmed, and after its implementation, the generation of hydrogen will significantly decrease, and the probability of a steam explosion will be minimal.

3. Optimization of the method for cooling corium in a melt trap

The comparison table summarizes all the information about the issues that have arisen during using water as cooling for the corium in the core catcher and possible solutions, Table 1.

Table 1. The comparison table about the issues and their possible solutions

The issue	Consequences of interaction with water	Way to solve the problem
Two-phase composition of the corium	Hydrogen explosion	Use of sacrificial materials to create conditions for gravitational inversion
The portioned output of corium from vessel	Steam explosion	Delay water supply to the core catcher

The core catcher of a light water reactor of the WWER type was chosen as the object of study in this work. For the first time, such a core catcher was installed during the construction of power units with WWER-1000 reactors at the Tianwan NPP. To date, the core catcher of the new WWER-1200 reactor, although it differs by minor structural changes and the materials used [22], the concept of corium cooling remains unchanged. It consists in diluting the corium with sacrificial materials for its further oxidation and the rise of the oxide part in order to reduce the intensity of hydrogen generation, reduce the volumetric energy release and increase the heat exchange surface with the trap casing while simultaneously supplying water to the surface of the corium.

Elimination of the problem of hydrogen generation in melt traps is planned due to inversion of the metal and oxide layers of the corium when sacrificial materials are dissolved in them. However, its implementation takes a certain amount of time, and the water supply should be started immediately at the moment the corium enters the trap due to the danger of the system going beyond the permissible limits (the beginning of the boiling of uranium dioxide) due to residual heat release in the corium [23]. As a result, during the period of time when the metal part is on the surface of the melt, water is supplied to it, which increases the process of increasing the generation of hydrogen, and given the portioned release of corium from the reactor pressure vessel, steam explosions.

On the basis of the foregoing, methods of melt cooling become very relevant, excluding the direct supply of water to the surface during the period of portioned release of the corium and until the completion of the gravitational inversion of the corium layers to prevent the likelihood of steam explosions and the generation of a large amount of hydrogen.

For this reason, the idea arose to use a non-aqueous coolant until the end of the gravitational inversion process to prevent steam explosions and generate a large amount of hydrogen. The proposed concept is based on the idea that when the corium enters the trap, the cooling material will move to its surface due to the density difference and will remove heat from the corium during the time period when water supply to the corium is undesirable. After the complete release of the corium and the completion of the process of inversion of its layers, water will begin to flow to its surface, and the selected material should undergo a phase transition of boiling and leave the trap. Thus, when using the proposed concept of corium cooling, it is supposed to reduce the probability of a steam explosion in the trap, as well as to reduce the intensity of hydrogen formation to a safe level.

In this regard, as candidate materials for the implementation of the proposed concept, materials with a lower density relative to the corium and having phase transition points significantly below the corium formation temperature should be considered.

One of the most optimal materials for cooling corium are metals. This article proposes to consider low-melting metals as a non-aqueous coolant. Since there is a possibility of accidental ingress of water into the area of melt localization, then when choosing a metal as a heat-removing material, in the first approximation, one should consider metals that are in the electrochemical series of metals to the right of hydrogen. However, few metals to the right of hydrogen in the activity series can be used as a cooling material not only in terms of physicochemical properties, but also for economic reasons. In this regard, metals were also considered, standing in the activity series on the left side of hydrogen.

To determine the most suitable candidate material, an analysis of the physicochemical properties of various metals was carried out, which were based on information from sources [24-25]. Table 2 lists some metals with a density below or approximately equal to the average corium density (ρ ~ 7315 kg/m3 [26]) that can be used as a cooling material. During analyzing the properties of metals, alkali metals were not considered due to their extremely high chemical activity.

Table 2. Properties of Candidate Metals

Name	Atomic number	Densityρ, kg/m^3	Melt temperature T_{melt}, °C	Boiling temperature T_{boil}, °C	Specific heat of melting λ, kJ/mol	Specific heat of boilingL, kJ/mol
Beryllium	4	1848	1278	2970	12.21	309
Magnesium	12	1739	650	1090	9.2	131.8
Calcium	20	1540	839	1484	9.2	153.6
Strontium	38	2630	769	1384	9.2	144
Barium	56	3760	729	1637	7.66	142
Aluminum	13	2698	660	2518	10.75	284
Titanium	22	4505	1670	3287	18.8	422.6
Antimony	51	6691	631	1635	20.08	195.2
Zinc	30	7133	420	906	7.28	114.8
Chromium	24	7190	1857	2672	21	342
Manganese	25	7210	1243	1961	13.4	221
Tin	50	7310	232	2620	7.19	296

According to the data given in Table 1, the most optimal metals for cooling the corium that meet the above requirements (the temperature of the corium can reach 2400 °C in the first hours after melting [27]) are antimony, alkaline earth metals (magnesium, calcium, strontium, barium), zinc and manganese.

The chemical activity of alkaline earth metals increases with increasing serial number. In this regard, among the noted alkaline earth metals for use in a melt trap, metals with a lower atomic number are considered the most acceptable, among which magnesium is the most optimal. The chemical activity of magnesium is much lower compared to other alkaline earth metals. This is because magnesium shares some chemical properties with the alkaline earth metals, but is otherwise markedly different from them. Nevertheless, magnesium remains a fairly active metal, so it should be considered as a last candidate.

Alternatives to magnesium are zinc and manganese. Zinc is more preferred as a candidate coolant due to the most optimal parameters (melting and boiling points), as well as its abundance in nature. In addition, zinc is inferior in chemical activity to alkaline earth metals, including magnesium, which is also an advantage. Another candidate material is antimony, which in its properties occupies an intermediate position between metals and nonmetals. The experiments are supposed to use the metallic modification of antimony. Antimony is distinguished by its low reactivity, acceptable melting and boiling points (more favorable relative to manganese), and unique chemical properties inherent in the so-called metalloids, which are of particular interest for their study when interacting with corium.

The use of zinc, and especially antimony and manganese, as possible coolants can cause difficulties in the sense that there is a possibility of their incomplete boiling out from the melt at the end of the inversion of corium parts. However, it is assumed that, being melted when heated from the corium, the sacrificial materials form a composition with a specific density of less than 6.4 kg/m^3 with the uranium-containing oxide part of the corium [28]. This means that due to the higher density, the rest of the coolant volume will also exchange position with the new mixture of sacrificial materials and the oxide part of the corium, thereby preventing dangerous hydrogen formation processes after the start of water supply to the melt.

4. Experimental studies of the proposed optimization of the corium cooling method

Based on the above, we can draw conclusions about the potential feasibility of the proposed cooling method. To confirm which, it is necessary to obtain information on the nature of the interaction of the selected materials with the corium, the efficiency of heat removal, etc. These issues require computational - theoretical and experimental study.

Thus, it seems appropriate to conduct a series of small- and large-scale experimental studies of the interaction between corium and candidate metal coolants in order to further develop recommendations on the possible use of the proposed cooling method in existing and future melt traps at nuclear power plants.

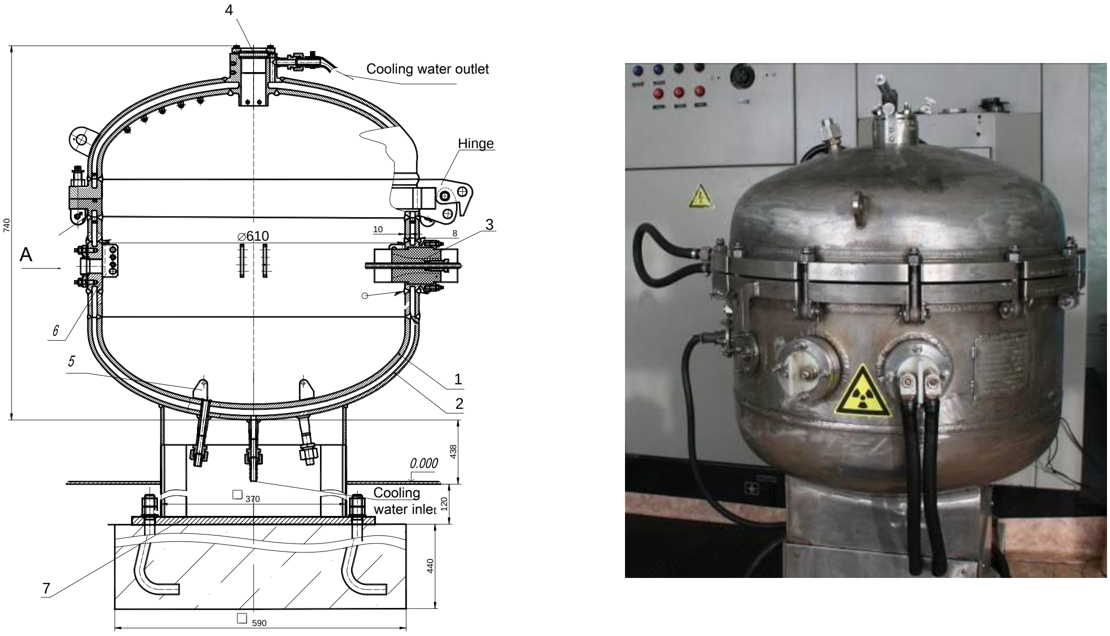
The method of physical modeling is the most effective way to confirm the operability of the proposed method, since it will allow simulating the situation of corium entering the melt trap from the reactor pressure vessel during a severe accident with a core meltdown. At the same time, experimental studies will be carried out on the VCG-135 test-bench and the Lava-B facility, created at the Institute of Atomic Energy Branch, RSE NNC RK [29]. The VCG-135 test-bench is designed to perform small-scale high-temperature material science studies of small-sized samples. The main components of the test-bench are a high-frequency electric lamp generator, a sealed, water-cooled working chamber with an inductor, a system for supplying and removing working gases into the working chamber, and an information-measuring system (IMS) of the test-bench. The appearance of the test-bench is shown in Figure 1.

Fig.1. Outer view of the VCG-135 test-bench.

The VCG-135 test-bench allows controlled heating of any small-sized samples in the working chamber to high temperatures (~ 3000 °C). At the same time, various studies are carried out at the test-bench to study the interaction of corium components with each other and with other structural elements, as well as its physicochemical and thermophysical properties. The scheme and outer view of the working chamber of the VCG-135 test-bench are shown in Figure 2.

In this case, VCG-135 is usually used mainly for small-scale experiments in addition to large-scale experiments performed at the Lava-B facility. Thus, the goal of future small-scale experiments on the test-bench is to determine the most optimal metal coolant for its testing at the Lava-B facility. Lava-B experimental facility includes two main functional units: an electric melting furnace (EMF) for preparing the melt of the prototype corium and a melt receiver (MR), which houses the experimental section for modeling the processes under study. The prototype corium, which consists of uranium dioxide, zirconium dioxide, zirconium and steel with a total mass of up to 60 kg, is melted in an induction electric melting furnace (EMF), and then merges into a melt trap equipped with a special heater to simulate residual energy release, which is placed in melt receiver (MR). The outer view and layout of the Lava-B facility is shown in Figure 3.

In experimental studies of severe accidents, a corium simulator, the so-called “prototype corium”, is used, a substitute whose characteristics are assumed to be quite close to the true ones. The essential difference between the prototypical and real corium is that the former is not a source of heat, that is, there is no self-sustaining radioactive decay in the prototypical corium [30].



a *b*

Fig.2. Outer view and scheme of the VCG-135 working chamber:
1 – inner casing of the pressure vessel; 2 – outer casing of the pressure vessel; 3 – inductor current lead; 4 – optical window; 5 – brackets for mounting the experimental assembly; 6 – electrode holders; 7 – base

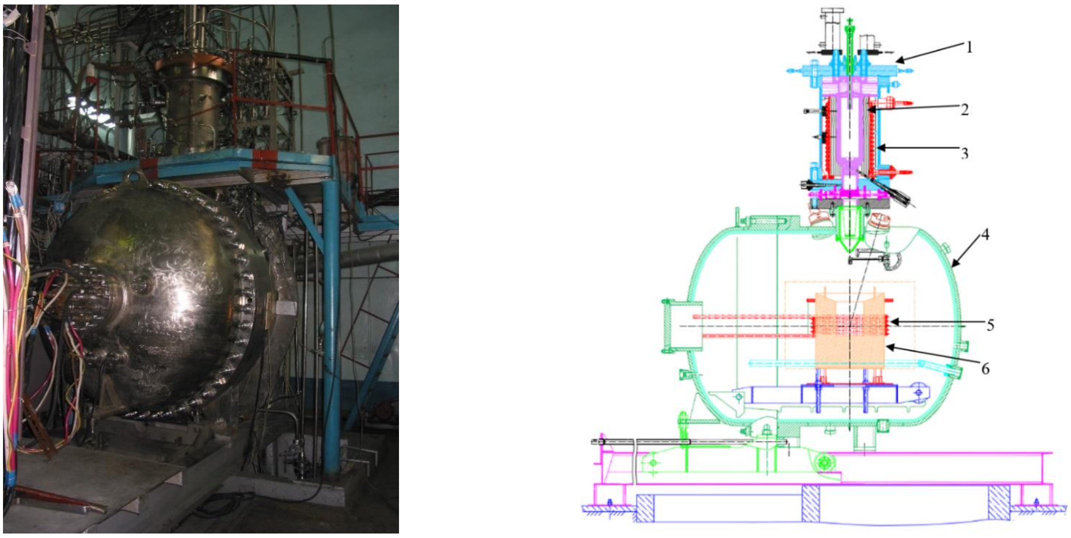


Fig.3. Outer view and scheme of the Lava-B facility: 1 – EMF (electric melting furnace), 2 – graphite crucible, 3 – EMF inductor, 4 – MR (melt receiver), 5 – MR inductor, 6 – concrete trap.

Therefore, to ensure conditions as close as possible to real ones, not only the correspondence of the composition of the prototype corium to the real corium should be taken into account, but also the presence of energy release in the melt to simulate a heat source in the corium. The importance of simulating the residual energy release is determined by the fact that the energy release in the melt significantly affects the nature of the interaction of its elements. At the Lava-B facility, depending on the goals and conditions, both induction and plasmatron heaters are used [31-32]. Many experiments are being carried out at the Lava-B facility to study the processes that accompany a severe accident in a light water power reactor [33–36]. The result of the work already carried out is the obtained valuable information on the possibility of managing a severe accident at different stages of its development.

Conclusion

The concept of a melt trap crucible device is predominantly the main choice in the construction of NPP passive safety systems. The operability of this concept was confirmed by both computational and experimental methods. However, this concept still has disadvantages associated with the initial stage of corium localization in the core catcher: the formation of explosive hydrogen during steam-metal reactions and the threat of steam explosions as a result of a batch outflow of corium from the reactor vessel.

In the scenario when water for cooling the corium is supplied immediately after the first portion of the corium enters the trap. This leads to the fact that at outflowing of the second portion of the corium (approximately 0.5 - 1 hour after the outflow of the first portion), a water pool is formed on the surface of the melt. In this case, when a high-energy melt falls into a container filled with water, there is a possibility of a steam explosion, as a result of which not only the device for trapping the molten materials of the core, but also the concrete burden with a sealed zone can be destroyed.

The second challenge is that corium is a mixture of two components that are immiscible with each other: metal and oxide. Due to the density difference between the two systems, the metal part of the corium is above the oxide part. This means that water is supplied directly to the metal part of corium. In that regard, it can be supposed that with the active interaction of water with the metal part of the corium, there is a possibility of the formation of a critical concentration of hydrogen and its detonation in the end. This means that the conditions of hydrogen safety and integrity of the containment cannot be reached.

To solve the above-mentioned disadvantages, part of the core catcher is filled with sacrificial material. Sacrificial materials are used to dilute the heat-generating oxide part of the corium in order to create conditions for the gravitational inversion of parts of the corium and reduce its high temperature. The experiments showed that the mutual dissolution of the sacrificial material and the melt occurs at a rate sufficient to implement the inversion of the oxide and metal layers in <1 h. Thus, the possibility of implementing the concept of gravitational inversion was experimentally confirmed, and after its implementation, water is supplied to the melt to cool it.

On the basis of the foregoing, methods of melt cooling become very relevant, excluding the direct supply of water to the surface during the period of portioned release of the corium and until the completion of the gravitational inversion of the corium parts. As a result, authors have the idea arose - to use a non-water cooler until the end of the gravitational inversion process to prevent steam explosions and generate a large amount of hydrogen. The most optimal coolants in this case are fusible metals with melting and boiling points, as well as a density below corium. The literature analysis of the physicochemical properties of known metals made it possible to select candidate metals that meet these requirements and can be used in melt localization devices during a severe accident at NPP.

Based on the above, we can draw conclusions about the potential feasibility of the proposed cooling method. To confirm which, it is necessary to obtain information on the nature of the interaction of the selected materials with the corium, the efficiency of heat removal, etc. These issues require computational - theoretical and experimental study. The method of physical modeling is the most effective way to confirm the operability of the proposed method, since it will allow simulating the situation of corium entering the melt trap from the reactor pressure vessel during a severe accident with a core meltdown. At the same time, experimental studies will be carried out on the VCG-135 test-bench and the Lava-B facility, created at the Institute of Atomic Energy Branch, RSE NNC RK.

Thus, it seems appropriate to conduct a series of small- and large-scale experimental studies of the interaction between corium and candidate metal coolants in order to further develop recommendations on the possible use of the proposed cooling method in existing and future core catchers at nuclear power plants.

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