THE STRATEGY OF MELT LOCALIZATION FOR VVER REACTORS UNDER SEVERE ACCIDENTS

Yu. Zvonarev, Yu. Semchenkov
NRC “Kurchatov Institute”
1, Academician Kurchatov square, Moscow, Russia, 123182
Zvonarev_YA@nrcki.ru; Semchenkov_YM@nrcki.ru

ABSRACT

The strategy of safety insurance at NPPs with VVER reactors under a severe accident (SA) conditions with fuel melting is discussed. For SA management, the NPP project provides for special engineered features aimed to protect the 4th safety barrier – the containment and to provide for the opportunity to put the plant into the stable controlled condition after an accident. The problem of the appropriate strategy is discussed for the melt localization and cooling under SA for VVER reactors of different power. The following two strategies have been analyzed: in-vessel melt retention (IVMR) by its external cooling and the employment of an ex-vessel core catcher (CC). The results on numerical modeling of the melt pool behavior at the reactor pressure vessel (RPV) lower head have been obtained as well as on thermal loading at the RPV wall. SA calculations have been performed by codes SOCRAT and ASTEC. Two- and three-layer configurations of the melt pool have been analyzed. For the comparison, the maximum heat flux density at the external surface of the RPV wall and the residual wall thickness were used. The obtained calculation results are considered that provide for potential prerequisites for IVMR strategy implementation in the case of SA at VVER reactors of lower and medium power. CC structure and basic models of HEFEST-ULR code developed by NRC “Kurchatov Institute” for modeling of the melt localization processes in CC are briefly described. Calculation estimations of the melt localization and cooling processes in CC for VVER-1200 reactor are presented. It is shown that it is necessary to employ an ex-vessel CC which performs its functions quite efficiently in SA management and provides for the melt localization and cooling reliably.

KEY WORDS
Severe accident, melt, IVMR strategy, core catcher

1. INTRODUCTION

More than 70 power units with VVER reactors of different power were built in the world, 58 of those are operated at the present time. Besides, 36 new power units are at different stages of development or building both in Russia and abroad including Europe. These are NPPs with VVER-1200 reactors of 3+ generation in Belorussia, Finland and Hungary. To achieve high competitive ability, new NPP projects must meet the most up-to-date safety requirements including lessons of the accident at NPP “Fukushima”, that is they must insure safety even in the case of SA with fuel melting. NRC “Kurchatov Institute” is a head of research in the development of projects including the issues of nuclear and radiation safety insurance as well as in SA management. NPP safety at all modes of operation is provided for due to the consistent implementation of the defense-in-depth concept that is based on the application of the system of physical barriers at the path of ionizing radiation and radioactive matters released into the environment. According to IAEA recommendations, an accident must be managed at the fourth level of defense-in-depth aiming to protect the last physical barrier – the containment in the case of SA with fuel melting.

At the present time, the following two strategies of an accident management for the melt localization and cooling are applied: the in-vessel melt retention due to the reactor vault water flooding for the RPV external cooling and the implementation of the ex-vessel core catcher (CC). CC is intended for SA radiation consequences mitigation down to the safe level in which case on a long-term core dryout, its destruction takes place with the further RPV melting through. Safety improvement is achieved due to the elimination of liquid and solid radioactive materials release out of CC boundaries that provides for the elimination of the containment damage.

The alternative concept of the IVMR in the case of an accident with the core melting through is also aimed at NPP safety improvement by the reduction of the containment damage risk and of the risk for the population and environment associated with that. In comparison with the ex-vessel CC application, the implementation of the IVMR concept has a series of essential advantages, first of all, regarding a power unit cost characteristics because this results in the reduction of the required equipment range, of expenditure for the equipment transportation and mounting, of the containment dimensions and of the respective quantity of consumed concrete and metal.

However, according to the preliminary estimates [1] performed in NRC "Kurchatov Institute", this strategy may be applied only for the VVER-type reactor of low and medium power, for instance, for VVER-600 reactor. To implement the concept of IVMR for VVER a higher power, the guaranteed elimination of accident scenarios with early core melting or the application of appropriate measures to increase a value of a heat flux critical density on the RPV external cooling.

Let us consider the opportunities for the implementation of both strategies of the melt localization and cooling in the case of SA with fuel melting at NPP with VVER-type reactors.

2. IN-VESSEL MELT RETENTION

The development basis of the system for the melt retention and RPV cooling is a proposition about the implementation of IVMR strategy due to the reactor external cooling in the course of SA. Proposals for this concept of the melt retention are based on the idea that the RPV lower head with additional external cooling is able to retain a damaged and molten core. For this case, a circuit for the natural circulation of cooling water flow must be provided (this is provided for by the reactor vault structure). The circuit must be designed so that a heat flux coming from the melt should be removed in the mode of water nucleate boiling on the RPV external wall. In such a case, a heat flux density must lower than a critical value of that.

The structure of high-temperature and heat-generating (due to the residual power) melt pool the configuration of which depends in its turn on the component and phase composition and component properties of the melt generated at the reactor lower head plays a key role in the distribution of thermal loading on the reactor wall. Studies performed within the framework of MASCA project [2] allowed to establish the principal regularities on the high-temperature core melt interaction with the in-vessel steel structures. It is established that steel melt extracts Zr and reduced U from the oxide melt at the predicted zirconium oxidation degree from 30% up to 70%. The composition of generated melt metal component and its density depend on steel mass involved into the process of interaction with the melt oxide component.

Uranium-zirconium ratio U/Zr is close to 1.2 for structures of VVER reactor cores. The mass of steel in-vessel devices (with no regard to the RPV steel) is assessed as a value close to that of the core mass. Completed estimates show that generation of the melt metal phase in the RPV in large volumes containing in its composition a basic fraction of uranium and zirconium sub-oxidized atoms should be expected as a result of the melt interaction with steel structures. The melt metal component density will be in all cases lower than that of the melt oxide component. Therefore, the configuration of a stratified melt pool with a metal phase on top is expected.

Thus, a so-called two-layer model of the melt stratified pool with an oxide phase at the bottom and a metal phase on top was considered for the calculation analysis of IVMR strategy implementation. Boundary conditions of the 3rd kind such as cooling water temperature and heat transfer coefficient were set at the RPV external boundary. A formula for heat transfer coefficient on water bubble boiling in a large volume was used for the calculation of the RPV external cooling. In the calculation course, the mode of heat transfer from the RPV external surface was controlled, that is, values of heat flux obtained in the calculation were compared with a value of critical heat flux (CHF). To evaluate CHF minimum values, this paper employs the results [3] obtained on water boiling in a large volume outside the RPV according to which CHF values are determined depending on the spatial orientation of the heat-releasing surface.

2.1. Calculation Results for VVER-600

Let us first consider the opportunity to implement the IVMR strategy in the case of SA with fuel melting for the reactor of medium power VVER-600. The calculation analysis of the melt pool behavior at the RPV lower head and of the core molten materials interaction with the RPV wall with external water cooling was performed according to the described methodical approach by the domestic severe-accident code SOCRAT. The simulation was limited to the RPV with corium in the lower head. Boundary and initial conditions were determined based on assessment calculations.

The analysis of obtained results allowed to determine and to describe typical stages of the melt retention process. This process stars in the calculation from generation of the quasi-equilibrium stratified melt pool. At the retention initial stage, two-layer melt localized in the RPV has the following characteristics: the metal layer high enthalpy, high heat spilling over from heat generation basic area in the oxide layer up to the metal layer through the interface without the boundary thermal resistance; high heat fluxes passing through the RPV wall in the metal layer area.

The RPV sub-melting resulted in the fact that the RPV wall residual thickness of 4 cm appeared to be sufficient for heat flux injection from the melt to water through the reactor wall and the further process proceeds with the gradual temperature decrease in the melt metal layer. Figure 1 demonstrates the configuration of the melt stratified pool and the temperature distribution in the melt and in the reactor wall at the moment of the wall minimum thickness achievement. The metal melt cooling down is accompanied with generation of a solidified metal crust at the wall and as the calculation shows and leads to the gradual transition of the whole process to the following significantly longer-term stage.

It follows from the obtained calculation results of heat flux density coming from the RPV surface along its height that heat flux density achieves the maximum value of 530 kW/m^2 at the height of about 1.6 m in the place of the melt metal phase contact with the wall that is significantly lower than CHF value. The heat flux critical value was not achieved in the calculation in any points of the RPV external surface. The minimum margin for this value (the ratio between CHF and maximum heat flux density) is 2.1 for VVER-600 reactor. The analysis of the implementation of IVMR strategy is considered in more detail in ref. [1].

Thus, the results of the completed calculation analysis of the IVMR process in the case of SA with fuel melting in VVER-600 allow for the conclusion that the strategy of IVMR due to the external cooling is quite feasible.

the ratio between CHF and maximum heat flux density

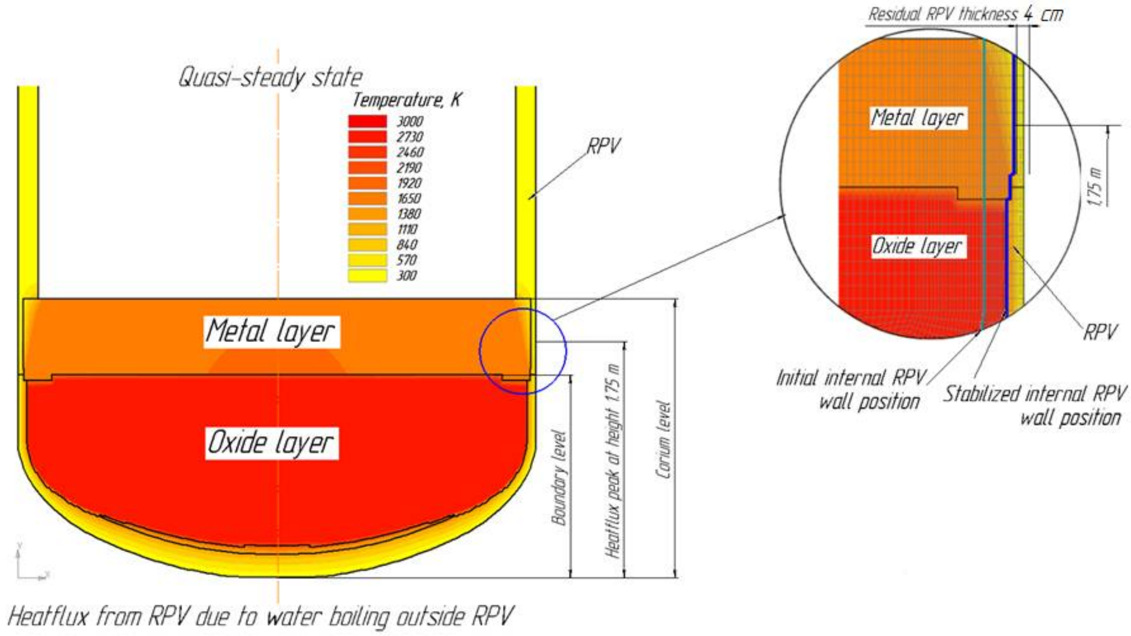

Figure 1. The Configuration of the Stratified Melt Pool and Temperature Distribution at the Moment of the RPV Wall Minimum Thickness Achievement.

2.2. Calculation Results for VVER-1000

The applicability of IVMR strategy for VVER-1000/V-320 reactors was analyzed for the case of SA progression according to the scenario with a guillotine rupture of 850 mm pipeline at the reactor inlet with a simultaneous power unit blackout and failure of diesel-generators. This scenario is characterized by fast core melting and the melt migration onto the reactor lower head with a high level of residual heat generation.

The major calculations were completed by the Russian code SOCRAT, the West European severe-accident code ASTEC was additionally employed that was preliminary accommodated and verified for the calculations of VVER reactors with regard to computational schemes, equipment characteristics, algorithms of safety systems' operation and database on material properties [4-6]. The calculations by both codes showed that heat flux density exceeded CHF in the area of the stratified melt metal phase contact with the reactor wall due to the so-called focusing-effect determined by a high thermal conductivity of metals in comparison with oxides. As an example, Figure 2 presents the results of calculation by code SOCRAT of heat flux maximum density variation in time at the RPV external surface. They demonstrate that heat flux density exceeds CHF value during the melt metal phase contact with the wall. This means the occurrence of departure from nucleate boiling that may result in the wall melt-through.

However, it is known that CHF may be significantly increased due to the application of special measures. The installation in the reactor cavity of a special deflector for the increase of a two-phase flow rate providing for CHF increase up to the necessary level or porous coating of the RPV external surface may serve as such measures. The opportunity should be also considered for the power unit equipping with additional emergency measure for the recovery of the reactor core lost cooling functions. This measure may be used for the melt cooling within the RPV aiming to prevent or delay the melt contact with the RPV wall that in its turn will result in the decrease of decay heat generation power.

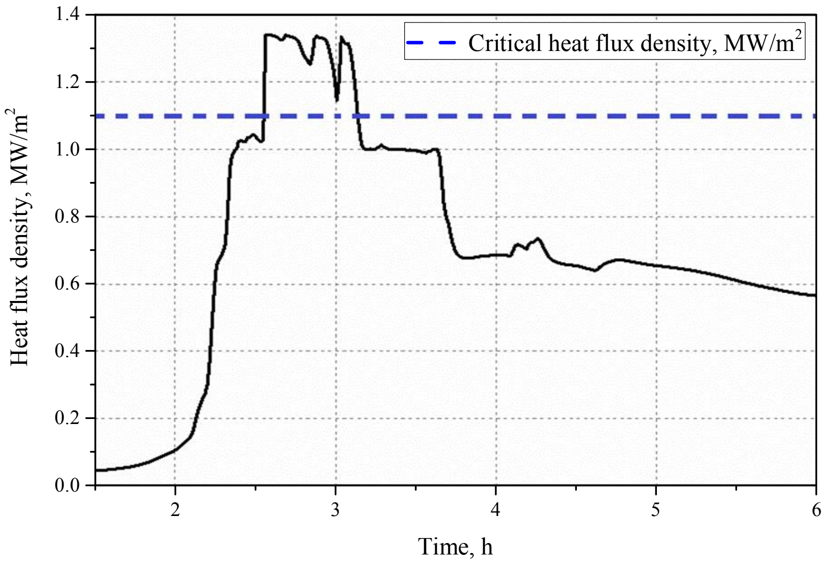

Figure 2. Heat Flux Maximum Density on the RPV External Surface.

To check the efficiency of some named factors, the impact on the IVMR process of such measures as water injection into the RPV and the deflector application were studied. According to the calculation results completed by code SOCRAT on the basis of realistic evaluation of residual power generation with regard to its decrease due to the release of volatile fission products, a combined action of such measures as heat-transfer intensification by a deflector (CHF increase) and water injection into the RPV allows to avoid the CHF achievement at the RPV external surface. In this case, minimal CHF margin is about 20% as Figure 3 shows.

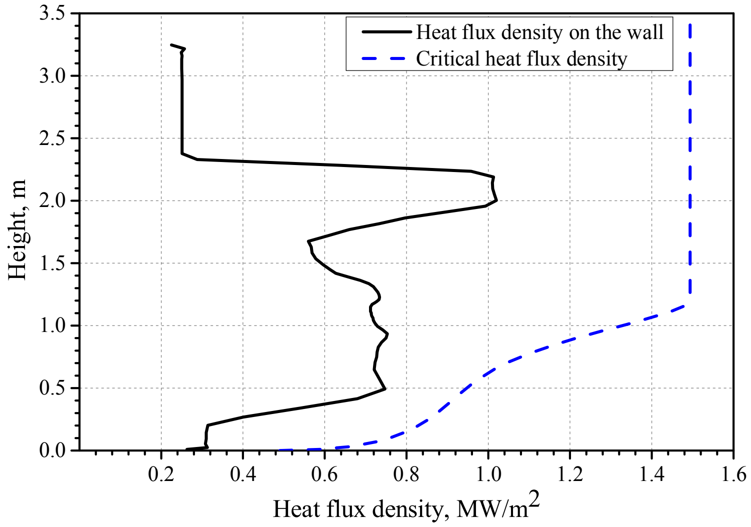

Figure 3. Maximum Heat Flux Density Distribution along the RPV Height – Calculation by SOCRAT Code with Regard to Measures on Heat-Exchange Intensification.

Sensitivity and uncertainty analysis was additionally performed for the process of the melt pool interaction with the RPV wall. 13 variants calculations were totally performed with limiting values of uncertain parameters such as a degree of materials oxidation, initial temperatures of the melt components, residual heat generation power and properties of materials under high temperatures. The results of completed variants calculations showed that the melt retention in VVER-1000 successfully took place in the majority of variants within the framework of studied values of uncertain parameters. CHF value excess was achieved only in one case of 13 ones, that is, on the integrated superimposition of most unfavorable values of understudied parameters. This result makes it possible to estimate the probability of successful IVMR by the value of the order of 85%. The mentioned calculation results for VVER-1000 are presented in [7].

Ref. [8] contains the results of experiments performed at the large-scale facility THS-15 in UJV Řež (Czech Republic) within the framework of the IVMR European HORIZON 2020 project. The experimental facility THS-15 was built to demonstrate the applicability of IVMR strategy for the removal of residual heat from corium for VVER-1000. The facility THS-15 recreates thermal-hydraulic conditions typical for VVER-1000 in IVMR course. For that purpose, the facility operating area simulates a specific form of a semi-elliptical lower head of VVER-1000 RPV.

Profiles of heat flux distribution on the RPV wall obtained in the calculations modeling IVMR process were set as boundary conditions for the performance of experiments. A part of support calculations was performed by SOCRAT code in NRC "Kurchatov Institute". Ref. [8] gives the results of 23 experiments. Heat flux maximum density achieved 2 MW/m^2. In all completed experiments, the wall cooling took place without of CHF achievement that demonstrated the opportunity for the successful implementation of IVMR strategy for VVER-1000 reactor conditions.

However, all mentioned above calculation and experimental results were obtained employing a two-layer model of the melt pool stratification typical for VVER-1000 reactor conditions in the course of quasi-steady-state process of heat removal from the melt through the reactor wall. In the course of the melt quasi-steady-state two-layer pool generation, the melt pool transient state may occur with three-layer stratification [9]. In this case, extremely high heat fluxes coming to the wall in the area of light metals should be expected.

Figure 4 demonstrates the calculation results for of heat flux distribution along the RPV height performed by codes SOCRAT and ASTEC for the melt three-layer model. According to the calculation results obtained by both codes, heat flux density profile has an extreme maximum in values of 1.8-2.4 MW/m^2 order in the area of lights metals contact with the wall that significantly exceeds maximum values of the two-layer model. In this case, it should be kept in mind that the process of the three-layer melt pool generation and behavior were not essentially studied. This fact in its turn determines a simplified approach to the development of relevant calculation models. Experimental data allowing for the estimation of a life time of the melt three-layer configuration for the reactor conditions with an acceptable degree of credibility are also lacking.

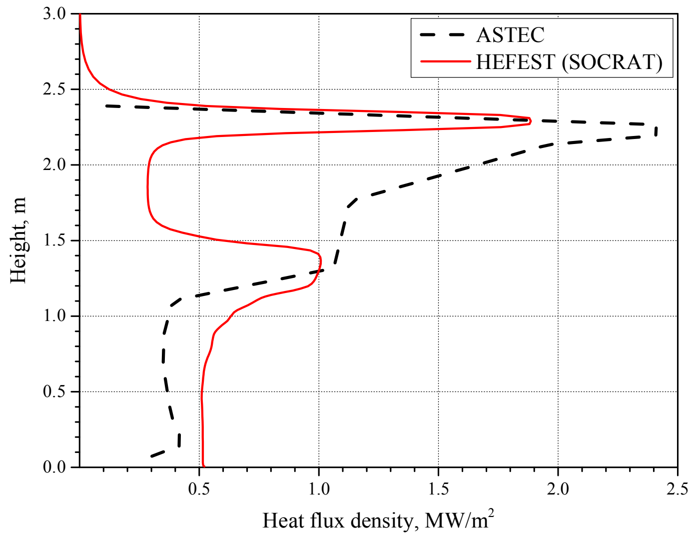

**Figure 4. Heat Flux Density Distribution along the RPV Height –
Calculation by SOCRAT and ASTEC Codes for the Melt Three-Layer Model.**

From the produced results it follows that the implementation of IVMR strategy is quite possible for VVER-600 reactor whereas the implementation of IVMR strategy for the reactor of a higher power such as VVER-1000 with no measures on the reactor external cooling intensification causes a series of concerns. To improve certainty of IVMR strategy estimate for VVER-1000 reactor, additional experimental-analytical studies are required aimed at studying the consistency in behavior of the melt of different configurations, in particular three-layer one, the experimental refinement of CHF values in the area of semi-elliptical RPV lower head of VVER-1000, study and optimization of measures for heat-exchange intensification under IVMR conditions. It is evident that IVMR strategy cannot be implemented for reactors of higher power such as VVER-1200 without the completion of mentioned additional studies.

3. IMPLEMENTATION OF EX-VESSEL CORE CATCHER

On the implementation of the melt ex-vessel localization strategy, the application of CC is provided for the basic functions of which are the receipt and localization of the melt inside its capacity as well as of the reactor core and structure solid material fragments, stable heat-transfer from the melt to cooling water and the melt assured cooling, the prevention of the melt escape beyond determined localization zone boundaries, the provision of the melt sub-criticality in CC, the mitigation of radioactive material release into the containment space and the mitigation of hydrogen generation.

The results of experimental studies completed within the framework of RASPLAV and MASCA projects [10, 2] in 1994-2006 in NRC "Kurchatov Institute" and other Russian organizations participated in these projects formed the basis for CC concept development and engineering design.

3.1. Core Catcher Design

A concept of a "dry" catcher of a crucible type was proposed on choosing CC concept and design. CC is located in a concrete cavity under the RPV lower head and is cooled from outside by water on the cavity flooding. CC interior volume is partially filled with comparatively low-melting iron and aluminum oxides of low density and with steel acting as sacrificial materials (SM). SM are intended for the melt full oxidation, its dilution aiming to reduce volumetric power generation density and to extend the surface of the melt heat-exchange with CC vessel cooled by water from outside. Figure 5 demonstrates CC general view.

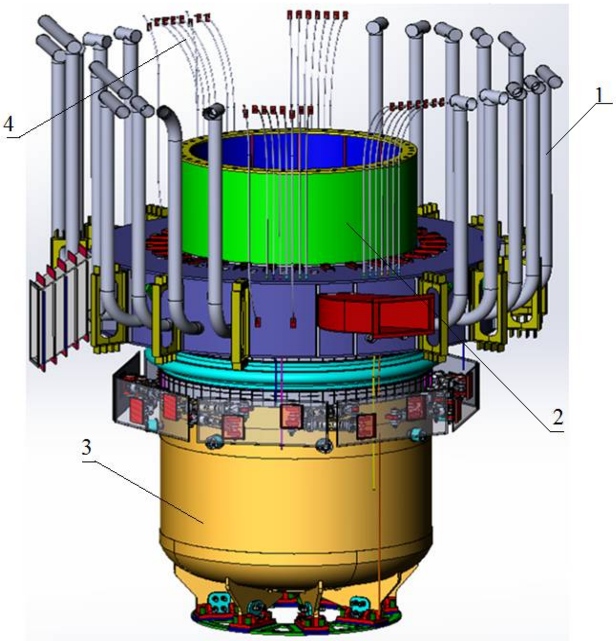

Figure 5. Assembled Core Catcher: 1 – Steam Discharge Pipes; 2 – Guiding Trumpet; 3 – Core Catcher Vessel; 4 – Connecting Lines of Instrumentation Sensors.

CC vessel is a cylindrical vessel of 6 m diameter and a conic bottom. The vessel has a double steel wall for the mitigation of thermal stress from the contact with a high-temperature melt. The gap between the vessel external and internal walls is filled with SM grains. As Figure 6 shows, cartridges with SM filler are located inside CC vessel.

According to the adopted concept, low-melting SM oxides must dissolve in the oxide system based on U–Zr–O coming from the reactor into CC. SM dissolution will result in the reduction of the melt temperature due to the combined endothermic effect as well as in the reduction of the melt melting temperature and of its density. Density reduction must provide for the inversion of the molten steel layer into the bath bottom part. In addition to that, specific density of residual heat-generation will be reduced and the area of external surfaces through which heat is removed will be extended due to the melt total volume enlargement. Reduction in the melting temperature of generated composition (U–Zr–O–low-melting alloy) will provide for a wider temperature range of the liquid melt pool existence and so that more intensive convectional heat removal to the surface caused by the natural circulation. Due to absorbing properties of SM in which gadolinium oxide is specially added, re-criticality is eliminated. To accelerate cooling of the melt pool generated in CC, the opportunity is provided for of cooling water feeding onto the melt pool surface, water comes into CC from outside through passive valves equipped with fused plugs.

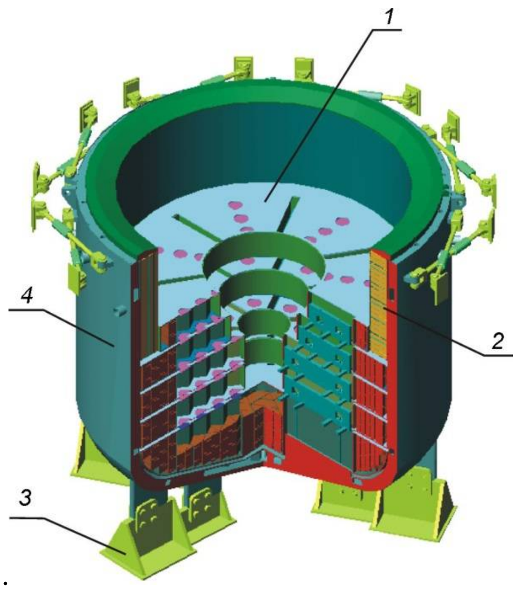

Figure 6. Core Catcher Vessel: 1 – Cartridges with SM Filler; 2 – High-Temperature Insulation; 3 – Vessel Support; 4 – Core Catcher Vessel Wall.

3.2. Specialized Code HEFEST-ULR

To analyze the melt behavior in CC, in 2010, NRC “Kurchatov Institute” developed a specialized code HEFEST-ULR in two-dimensional axisymmetric statement with an “end-to-end” calculation technique based on a full set of mathematical models of all basic physical processes in CC. The code was created by the modification and elaboration of HEFEST module of severe-accident code SOCRAT intended for the description of the melt behavior at the reactor lower head by inclusion a series of additional mathematical models of physics-chemical interaction of the melt components with SM, of gas release, boundary cooling and others. Description in detail of the melt behavior models enabled in HEFEST module is given in ref. [11]. Below, you will find description of only those mathematical models related to physics-chemical interaction of the melt components with SM additionally developed for HEFEST-ULR module.

Physics-chemical interaction of the melt components with SM starts at a definite temperature under the conditions of two materials contact and includes heating, melting, dissolution, decomposition, chemical reactions of SM and melt components. Chemical reactions in CC are divided in two groups: taking place close to the melting front and taking place in the melt volume on mixing of reaction products in the melting front and of unreacted SM with the melt basic mass. These reactions are considered separately in the developed model, in this case, the first group of reactions influences the condition of a low volume in the melting front and the second group of those influences the whole melt pool.

On the model elaboration, the following assumptions were made:

- Heat flux delivered to SM surface is determined both by heat released in the reaction layer in the melting front and by heat-exchange on free convection. Difference in temperatures in the reaction layer and the surface typical temperature are parameters setting flux value;
- Heat flux is removed from the reaction layer in the melting front to the melt volume during free-convection heat-exchange. Intensity of that is determined by difference in temperatures of the reaction layer and the melt volume as well as by SM surface orientation;
- The reaction layer mass-exchange in the melting front between SM and the melt consists in leak-in of iron oxides and sub-oxidized Fe from SM into the reaction layer, in Zr and steel components (Cr, Ni, Fe) coming from the melt. Chemical reaction products and SM unreacted components (aluminum oxide, excess of sacrificial steel or of iron oxide) come into the melt from the reaction layer. In the case of stratified melt, they are distributed into the appropriate layers.

After the completion of reactions in the melting front and before mixing of reaction products with the melt pool, similar reactions taking place in the volume are modeled as well as the reaction of iron substitution by zirconium in FeO.

HEFEST-ULR code contains also models of noncondensable gases: oxygen (due to hematite reduction) and hydrogen (due to dehydration of calcium compounds contained in concrete and to further oxidation of the melt metal components by liberated water vapor).

To verify HEFEST-ULR code models, analytical tests, cross-verification by best estimate codes and direct experimental data were employed that allowed validation of models describing all the most important thermal-physics and physics-chemical processes taking place in the course of the melt localization and cooling in CC. The results of HEFEST-ULR code validation are presented in [12].

3.3. Calculation Results for Processes in CC for VVER-1200

Below, the results of calculation analysis of CC operation efficiency are presented for NPP with VVER-1200 reactor. The calculation analysis was performed by HEFEST-ULR code for SA with long-term loss of all alternate current sources and two channels of steam generator passive heat removal system failure due to unfitting of power-operated relief valve. Parameters and component structure of the melt entry into CC were determined by SOCRAT code.

The analysis shows that the melt entry into CC starts in 43 hours after the accident initial event. Within the first hour after the start of the melt entry into CC, the melt structure includes only the metal phase (Figure 7, a). During this period of time, steel interacts with SM causing its partial melting. Shortly after the first portions of oxide melt containing UO_2 enter CC, a heavy oxide fraction gravitates into the lower part of the melt pool, that is, the melt pool "direct" stratification takes place (Figure 7, *b*). The melt interaction with SM is accompanied with the oxide phase saturation by light oxides and its density is reduced. In 2.2 hours after the start of the melt entry, the melt pool inversion takes place and its oxide phase migrates upward (Figure 7 c), cooling water is fed onto the melt pool surface. The melt surface temperature reduces rapidly down to ~1400 K with generation of a solid crust.

According to the calculation, in 3.9 hours after the start of the melt entry into CC, CC vessel internal wall and SM filler in the interstitial space are molten through. The melting front moves to CC vessel and approaches close by the vessel external wall at the time moment of 48.3 hours. The melt front propagation in the radial direction is terminated. Heat is efficiently removed from the melt to cooling water through CC wall.

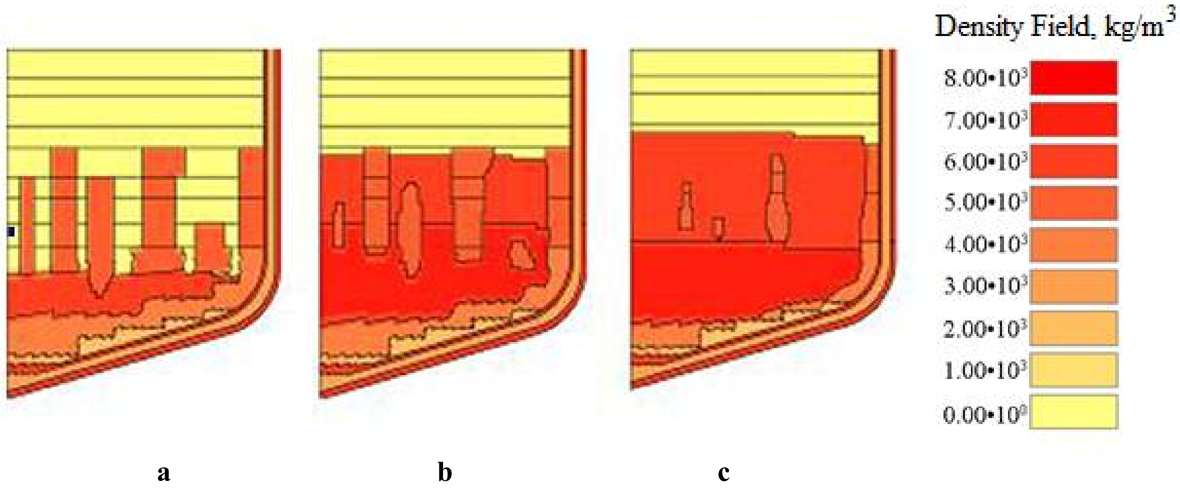

Figure 7. The Melt Interaction with SM in CC. Density Field, kg/m^3: a – The Melt First Portion Entry (in 43.0 hr); b – The Melt Pool Direct Stratification: the Metal Phase is at the Top, the Oxide Phase is at the Bottom (in 44.2 hr); c – The Melt Pool Inverse Stratification: The Oxide Phase is at the Top, the Metal Phase is at the Bottom (in 45.2 hr).

The calculation results presented in Figure 8 show that the maximum value of heat flux at CC vessel external surface stated in the calculation is equal to 0.3 MW/m^2. This corresponds to quadruple departure from nucleate boiling at CC external surface. Ref. [13] gives in more detail the calculation results justifying CC for VVER-1200 reactor.

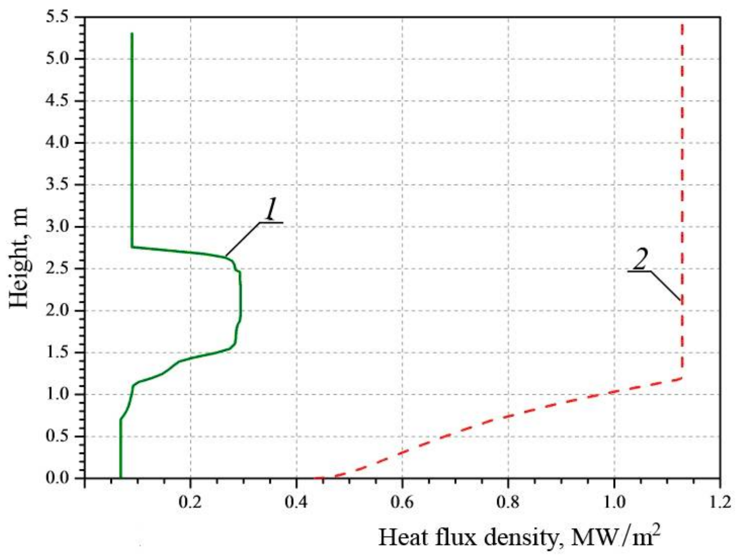

Figure 8. Heat Flux Distribution along the RPV Height: 1 – The Maximum Heat Flux Density at CC Vessel External Surface; 2 – CHF.

Hydrogen generation mitigation in the course of the melt localization and cooling is one of CC important functions that is achieved by Zr oxidation with oxygen generated due to reduction of hematite (mineral form of iron oxide Fe_2O_3) specially contained in SM composition. Figure 9 demonstrates the results of hydrogen generation calculation for three SA scenarios at VVER-1200: two of those correspond to LB LOCA of 850 mm diameter break at the reactor inlet and outlet and one corresponds to SB LOCA from hot leg of 70 mm diameter.

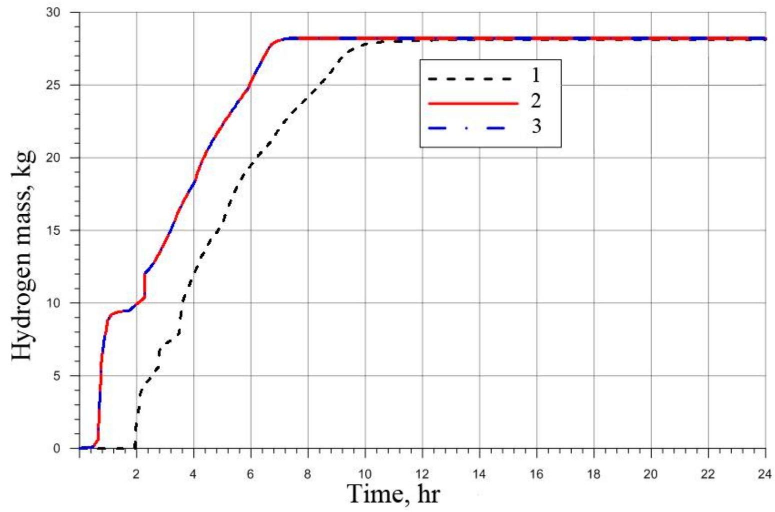

Figure 9. Hydrogen Generation in CC in the Course of SA: 1 – LB LOCA of 850 mm in the Reactor Cold Leg; 2 – LB LOCA of 850 mm in the Reactor Hot Leg; 3 – SB LOCA of 70 mm in the Reactor Hot Leg.

The appropriate moment of time of the RPV wall destruction and of the start of the melt entry into CC was adopted as timing point in the calculation analysis for each of scenarios. Hydrogen is generated basically on zirconium oxidation by water residing in concrete and cement that are used in limited quantities in the filler in CC vessel. In all cases under consideration, hydrogen generation totally does not exceed the value of 30 kg that is many times as low then hydrogen quantity which could be generated on the melt interaction with the reactor vault concrete in CC absence.

Thus, it is demonstrated with an example of the calculation analysis of the melt behavior in CC for NPP with VVER-1200 reactor that CC is quite efficient in the melt localization and cooling. That particular CC is implemented for the management of a severe accident with fuel melting in new projects of NPPs with VVER reactors of increased power such as NPP-2006 and VVER-TOI for the following NPPs: Novo-Voronezh NPP-2, Leningrad NPP-2, Kursk NPP-2 as well as for a series of NPP projects to be built abroad: NPP “Akkuyu” in Turkey, NPP “Rooppur” in Bangladesh, Belarusian NPP in Ostrovets, NPP “Hanhikivi-1” in Finland, NPP “Paks-2” in Hungary and NPP “El-Dabaa” in Egypt.

4. CONCLUSIONS

The calculation analysis results are presented justifying the management strategy choice for SA with fuel melting for VVER reactors of different power. The cases of the implementation in NPP projects either ex-vessel CC or of the implementation of IVMR strategy are considered. Calculations were performed by the following two system severe-accident codes: Russian SOCRAT code and West-European ASTEC code as well as by the specialized Russian HEFEST-ULR code.

The obtained results allow for the following conclusions:

- The implementation of IVMR strategy due to the RPV external cooling is feasible for VVER-600;
- The implementation of IVMR strategy for VVER-1000 requires additional experimental-analytical studies;
- For the management of SA with fuel melting, CC should be applied for VVER of increased power (AES-2006 project with VVER-1200 and VVER-TOI with VVER-1300).

Studies of consistency in the behavior of melt of different compositions, in particular three-layer one, experimental specification of CHF in the area of semi-elliptical RPV lower head of VVER, studies and optimization of measures for the reactor external cooling intensification under IVMR conditions should be noted as the most up-to-date additional experimental-analytical IVMR studies for VVER-1000.

REFERENCES

1. Yu. Zvonarev, M. Budaev, A. Voltchek, et al., "Numerical Investigation of the In-Vessel Corium Retention During Severe Accidents on VVER NPPs," *Voprosy Atomnoi Nauki I Tekchniki: Fizika Yadernykh Reactorov (available in Russian, translated in Physics of Atomic Nuclei (Yadernaya fizika)*, **2**, pp. 93-107 (2012).
2. D. Tsurikov, "Masca 2 Project: Major Activities and Results," *Proceedings of the Masca 2 Seminar,* Cadarache, France, October 11–12, (2007).
3. J. Yang, F.B. Cheung, J.L. Rempe, K.Y. Suh, S.B. Kim, "Correlations of Nucleate Boiling Heat Transfer and Critical Heat Flux for External Reactor Vessel Cooling," *ASME Summer Heat Transfer Conference. Preprint INEEL/CON-05-02604,* July 17–22, (2005).
4. Yu. Zvonarev, M. Budaev, V. Kobzar, A. Volchek, "ICARE/CATHARE and ASTEC Codes Validation and Application to Safety Analysis of NPPs with VVER," *Proceedings of the International Congress on Advances in Nuclear Power Plants (ICAPP'05),* Seoul, Korea, May 15–19, (2005).
5. Yu. Zvonarev, A. Volchek, V. Kobzar, P. Chatelard, J.P. Van Dorsselaere, "ASTEC and ICARE/CATHARE Modelling Improvement for VVERs," *Nucl. Eng. and Design* **241**(4), pp. 1055-1062 (2011).
6. Yu. Zvonarev, A. Volchek, V. Kobzar, M. Budaev, "ASTEC Application for In-Vessel Melt Retention Modelling in VVER Plants," *Nucl. Eng. and Design,* **272**, pp. 224-236 (2014).
7. J. Zdarek, L. Krhounek, D. Batek, Yu. Zvonarev, A. Volchek, V. Kobzar, M. Budaev, "Assessment of In-Vessel Melt Retention Possibility for VVER-1000/320," *Proceedings of 6th European Review Meeting on Severe Accident Research (ERMSAR-2013),* Avignon, France, October 2–4, (2013).
8. J. Zdarek, D. Batek, V. Krhounek, J. Bulak, P. Mackerle, "D 4.3 Interim report on full scale tests (WP4 – HORIZON 2020 IVMR)," pp. 29, Řež, Czech Republic, (2018).
9. F. Fichot, L. Carénini, M. Sangiorgi, S. Hermsmeyer, A. Miassoedov, S. Bechta, J. Zdarek, D. Guenadou, "Some considerations to improve the methodology to assess In-Vessel Retention strategy for high-power reactors," *Annals of Nuclear Energy*, **119**, pp. 36–45 (2018).
10. V. Asmolov, "RASPLAV Project Major Activities and Results", *Proceedings of CSNI/NEA RASPLAV Seminar 2000*, Munich, Germany, November 14–15, (2000).
11. N. Mosunova, V. Strizhov, A. Philippov, "Melt Modeling in VVER Vessel in SOCRAT/HEFEST Code," *Izvestiya RAN. Energetika (available in Russian)*, **3**, pp. 43–63 (2010).
12. Yu. Zvonarev, V. Kobzar, I. Melnikov, A. Philippov, "Verification of HEFEST-ULR Code for Substantiation of Core Catcher Efficiency," *Proceedings of the 7th International Scientific and Technical Conference "Safety Assurance of NPP with VVER" (ISTC-2013),* Podolsk, Moscow Region, Russia, May 28–31, (2013).
13. Yu. Zvonarev, D. Tsurikov, V. Kobzar et al., "Computational analysis of the core catcher efficiency for the VVER-1200," *Voprosy Atomnoi Nauki I Tekchniki: Fizika Yadernykh Reactorov (available in Russian, translated in Physics of Atomic Nuclei (Yadernaya fizika)*, **1**, pp. 68-78 (2010).