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Research Article

New technical solutions for the design of NPP passive safety systems*

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Abstract

The paper describes the new principle of passive NPP safety systems designing, in which the natural circulation of working fluid or gas is replaced by forced circulation in order to increase it's capacity. The energy required by the system is converted from the emergency process itself, which this system resists when performing a given safety function. The goal is to expand the variety and capacity of passive NPP safety systems in order to optimize and reduce costs of NPP power units with various types of reactors while increasing the safety level. The proposed technical solutions are based on the use of direct non-mechanical conversion of the energy, comprised in emergency process, to electricity, and then to mechanical energy of hydraulic machine for working medium moving in a forced circulation mode. To demonstrate the proposed principles, the following technical solutions have been considered:

- new passive electrochemical hydrogen recombiner for NPPs with light water reactors. Application of new techniques allowed increasing the performance by weight of the recommended hydrogen simultaneously with increasing the hydrogen torch threshold, as well as other important characteristics;
- passive emergency core cooling system for heavy liquid metal cooled reactors. Application of new techniques allowed increasing the core remove heat capacity in order to scale down the main equipment;
- passive system for in-vessel core melt retention of Pressurized Water Reactors of high thermal capacity (more than 3000 MWe). Application of new techniques allowed increasing the system thermal capacity in order to be able to apply to high thermal power reactors like VVER-1000 and more.

Keywords

passive safety systems, hydrogen safety, emergency core cooling, hydrogen recombiner, core melt

Introduction

The safety of modern NPPs is ensured through the use of active and passive safety systems, the best possible combination of which is adopted for the design with regard for the balance of construction costs and compliance with safety standards and criteria. At the same time, there is no broad variety of technical solutions operation of passive safety systems is based on. Used largely are natural circulation of the process fluid or gas, gravity force and the mechani-

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cal energy stored. The most commonly used passive safety systems are those based on the principle of natural circulation of the process fluid or gas. The major disadvantage of such systems is low velocity of the fluid flow in the natural circulation mode, this affecting the system power which may turn out to be insufficient for performing a given safety function, and also having negative effect on the inertia and stability of characteristics in the process of the system operation as a whole. As a result, to provide the power required for the system to perform a given safety function, it needs to be scaled up with increasing the weight and dimensions of the system and its components, this expected to worsen simultaneously other characteristics also important to the safety function. The development and justification of new technical solutions for operating passive safety systems of increased power having low inertia properties and stable functional characteristics independent of external factors (with smaller specific weight and dimensions) is essential to increasing the safety and economic efficiency of NPPs in operation and under development.

General concept of the proposed technical solutions

In accordance with the definition in "General Provisions for Determining the Safety of Nuclear Power Plants" (NP-001-15 2015), "A passive system (component)" is a system (component), operation of which is associated only with the event that causes it to operate and does not depend on operation of another active system (component). In terms of design characteristics, passive systems (components) are divided into passive systems (components) with mechanical moving parts and passive systems (components) without mechanical moving parts. In accordance with the IAEA classification (IAEA-TECDOC-626 1991), "Passive component is a component which does not need any external input or an external power source to operate, and passive system is a system composed entirely of passive components which uses active components in a very limited way to initiate subsequent passive operation". In accordance with this classification, in terms of their design peculiarities, passive systems are divided into the following categories: A, B, C, D. To create passive safety systems with improved functional characteristics that meet Russian and international regulatory requirements, a new principle of operation is proposed, in which natural circulation of the process fluid or gas will be replaced by forced circulation of a greater intensity while preserving the overall passive mode of the system operation. Forced circulation of the process fluid is enabled by using the stored internal energy from the emergency process converted to electric energy without the use of machines and, then, to mechanical energy from the drive of a hydraulic machine for moving the process fluid or gas. The serviceability and scalability of the proposed principle is demonstrated using an example of technical solutions for the following passive systems:

- a passive electrochemical hydrogen recombiner (PEHR) intended for nuclear power plants with light water reactors;
- a passive emergency core cooling system (ECCS) for liquid metal cooled reactors;
- a passive system for in-vessel core melt retention passive system of a large pressurized water reactor.

Passive electrochemical hydrogen recombiner

In accordance with the concept of ensuring hydrogen explosion safety of NPPs, the emergency hydrogen removal system uses equipment the action of which is based on flameless catalytic recombination of hydrogen with oxygen in the presence of a platinum catalyst. This is an exothermic reaction accompanied by the release of heat in the amount of 124 MJ per kilogram of recombined hydrogen. The method for the flameless catalytic recombination of hydrogen with oxygen is implemented using passive autocatalytic hydrogen recombiners (PAR). Among the variety of currently existing PAR designs developed in different countries, including the FR (AREVA, France), the GRS and the NIS (Ingenier GmbH, Germany), the REPAK (SULZER, Switzerland), the AECL (Canada), and the RVK (Russia), only the RVK-500, RVK-1000 and FR90 designs have been certified and used at NPPs in Russia. All PAR designs are nearly identical and comprise a stainless steel housing with a catalytic unit installed inside it, via which a hydrogen-air gas mixture is pumped in the natural circulation mode, and air chimney for the gas mixture removal. The difference consists in the catalytic unit design. The FR90 catalytic unit is formed by a set of metal plates with a catalytic coating installed in parallel along the vapor-gas flow. The RVK's catalytic unit consists of a set of ceramic rods with a catalytic coating (additionally, their surface also has a protective hydrophobic coating) installed in parallel along the vapor-gas flow. The hydrogen-air gas mixture in the natural circulation mode enters the catalytic unit, where hydrogen and oxygen recombine on the catalyst surface to form water vapor and release heat, which is used then to increase the temperature of the catalyst and the gas mixture. An increase in the gas mixture temperature promotes the development of natural circulation through the PAR cooling so the catalyst and ensuring the supply of hydrogen onto the catalytic surface. Under certain conditions, the catalyst can be heated up to the temperatures capable to cause the ignition of the hydrogen-air mixture pumped through the PAR. In the event of a severe accident with the core melt and the subsequent corium interaction with concrete (in the absence of a core catcher), a major hydrogen release is possible. According to different estimates, such an accident at an NPP with a VVER-1000 reactor is expected to lead to up to 3000 kg of hydrogen to escape to beneath the containment. To process such amount of hydrogen, when justifying the hydrogen safety of NPPs, the required number of PAR s and their installation points are calculated. The initial data for such calculations are the following key PAR characteristics:

- starting value, vol. % (the minimum volumetric concentration of hydrogen at which the PAR starts to operate steadily);
- capacity, kg/h (the PAR capacity in terms of recombinable hydrogen per unit time);
- specific capacity, kg/(m^{2}h) (capacity per unit area of the catalytic surface);
- “ignition” threshold, vol. % (the threshold volumetric concentration of hydrogen that characterizes the transition from the flameless recombination mode to the “ignition” mode with the open flame release to beyond the PAR housing).

Table 1 presents the PAR characteristic shown by manufacturers in the equipment specifications (“Passive catalytic hydrogen recombiner RVK-500, RVK-1000”. Specifications RET-101.00.000 TU; “Passive catalytic recombiners (PAR) of the FR90/1-1500 and FR90/1-750 types”; Specifications from JSC “NPK Elliron”, TU 3442-002-52787498-09).

Table 1. Key characteristics of PARs

	RVK-500	RVK-1000	FR90/1-750
Length, mm	334	650	800
Width, mm	226	220	326
Height, mm	950	1400	1400
Weight, kg	25	40	60
Capacity, kg/h	0.066	0.157	2.4
Catalytic surface area, m^2	0.6	1.2	5.7
Specific capacity, kg/(m^{2}h)	0.11	0.13	0.4
“Ignition” threshold (% vol.)	11	11	8

There are some restrictions with respect to the use of PARs to ensure hydrogen safety of NPPs.

Low capacity

Using natural circulation of a hydrogen-air mixture with a low circulation rate (not more than 1–2 m/s) leads to a small specific capacity of the PAR in terms of the recombined hydrogen mass. In accordance with Table 1, the RVK-1000’s capacity is 0.157 kg/h with a total catalytic surface area of 1.2 m^2, and the FR90/1-750’s capacity is 2.4 kg/h with a total catalytic surface area of 5.7 m^2. A small specific capacity leads to the need for increasing the catalytic surface area to ensure the removal of hydrogen released during a severe beyond design basis accident (SBDBA). This requires increasing either the PAR weight and dimensions or the number of PARs installed per NPP unit. Thus, as provided by the VVER-TOI design, the emergency hydrogen removal system comprises 207 PARs (200 RVK-1000s and 7 RVK-500s) with an integral capacity of 31.9 kg/h, and the Novovoronezh NPP II’s unit is equipped with 196 PARs (184 RVK-1000s and 12 RVK-500s) with an integral capacity of 29.7 kg/h (with a hydrogen concentration of 4 vol. % and 0.15 MPa). The report from the Scientific and Engineering Center for Nuclear and Radiation Safety (SEC NRS), “Analysis of the Activities for Justifying the Design characteristics and Performance of Passive Catalytic Recombiners (PAR) in Conditions of Severe Beyond Design Basis Accidents for NPP Units with VVER Reactors” (No. DNP 4-1275/2017), points out the integral capacity of the emergency hydrogen removal system is insufficient, specifically taking into account the need for considering the interaction of corium with concrete (the core catcher’s sacrificial material) and the oxidation of zirconium in the SNF cooling pool. The weight of one RVK-1000 is 40 kg, while PARs are installed within the containment rooms, normally, as high as possible, this leading to an increased mechanical load on the containment and affecting adversely its strength and integrity, specifically in the event of seismic and other external loads. Small capacity of existing PARs stems from the low rate of hydrogen delivery to the catalytic surface with natural circulation of the hydrogen-gas mixture. The maximum possible capacity of the catalytic surface is much higher than that in PARs (Avdeenkov et al. 2023).

Low “ignition” threshold

As shown in Table 1, the RVK ignition threshold is 11% and the FR90 ignition threshold is 8%. There are such potential scenarios for the SBDBA development at NPPs with VVERs, in which the average volumetric concentration of hydrogen in some of the containment rooms may exceed 12%. A low “ignition” threshold also means an insufficient margin of the critical parameter that limits the region for the recombiner to perform potentially its safety function. These circumstances are important given the processes of hydrogen stratification in large rooms with the occurrence of regions with an increased volumetric concentration. Within such regions, the PAR as such can initiate deflagration and detonation of the mixture. The low “ignition” threshold of the existing PARs stems from the low rate of natural circulation of the hydrogen-gas mixture through the PAR. “Ignition” is initiated by the catalyst being heated above the volumetric “ignition” temperature of the hydrogen-air mixture (530–550 °C) due to the heat release in the process of hydrogen recombination.

Impact of external factors on the key parameters of PARs

The PAR parameters given in Table 1 are valid only for the conditions under which they were obtained in the course of the PAR bench testing. They do not take into account many factors that occur in the real conditions of a SBDBA, for example, the actual hydrodynamic situation in the deployment area. Thus, the downward and upward flows of the hydrogen-containing gas mixture suppress (disturb) the natural circulation through the PAR, which affects substantially its actual flow rate characteristic, the capacity and the “ignition” threshold value. With natural circulation of the hydrogen-air mixture used in the PAR, the recombiner characteristics, on the basis of which the safety of NPP units is assessed, depend on the changeable external accident conditions. This leads to an uncertainty both when justifying safety using modern calculation tools, and when ensuring safety in actual emergency conditions.

A simultaneous increase in the specific capacity of the PAR and in the “ignition” threshold achieved via upgrading the existing PAR design is impossible due to the constraints inherent in the principle of operation as such, which is based on the direct hydrogen recombination with oxygen on the catalyst surface with natural circulation of the hydrogen-air mixture. To eliminate the described constraints, the design of a passive electrochemical hydrogen recombiner (PEHR) has been proposed. This technical solution consists in using a hydrogen fuel cell technology as part of an electrochemical unit (Zaryugin et al. 2016). The concept of a hydrogen fuel cell suggests that hydrogen is removed using the hydrogen dissociation reaction on the anode followed by recombination with oxygen on the cathode separated by an ion-conducting membrane. In this case, a portion of the energy released is converted to electrical energy and then to the mechanical energy of the fan drive which pumps the hydrogen-oxygen mixture through the PEHR. There will be less anode generated heat than in the event of the catalytic element of the existing PARs. A growth in the pumping rate (mass flow of hydrogen) leads to an increase in the PEHR specific capacity in terms of the recombined hydrogen production and to more thermal energy released to be removed with the exhaust gas mixture while there is a decrease in the catalytic element temperature as the “ignition” threshold increases respectively. Fig. 1 presents generalized diagrams of the PEHR (top) and the electrochemical unit.

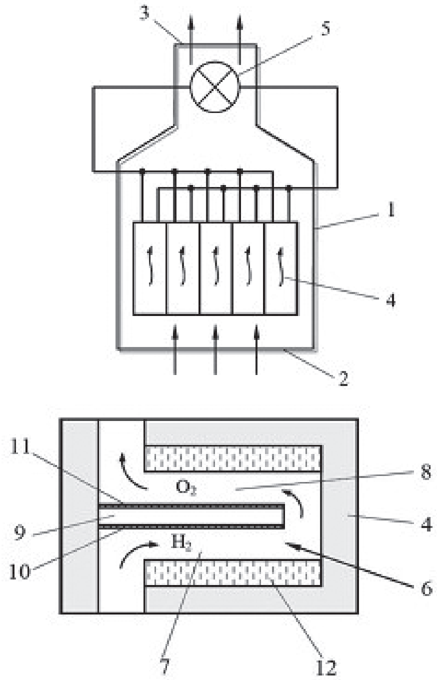

Figure 1. Generalized diagram of a PEHR: 1 – recombiner housing; 2 – inlet; 3 – outlet; 4 – catalytic unit; 5 – fan; 6 – hydrogen mixture flow channel; 7 – channel inlet; 8 – channel outlet; 9 – membrane; 10 – anode; 11 – cathode; 12 – radiator.

The PEHR shown in the diagram comprises a housing 1 made of stainless steel in the form of a vertical directed shroud having an inlet section 2 and an outlet section 3. The housing is designed such that to form an upward gas mixture flow through the device. Inside the housing, there are electrochemical units 4 and a compressor 5. As shown in the generalized diagram, the electrochemical unit comprises a channel 6, which has an inlet area 7 and an outlet area 8. Inside the channel 6, there is a hydrogen fuel cell 9. Since the electrical energy for actuating the fan and creating forced circulation of the gas mixture through the PEHR is generated due to the energy of the hydrogen redox reaction on the catalytic surface of the hydrogen fuel cell, the system operation depends only on if there is hydrogen and does not require any other control actions or an external energy source.

Passive emergency core cooling system (ECCS) of a heavy liquid metal cooled reactor

In accordance with the BREST OD-300 reactor safety concept, the ECCS operates based on a passive principle, that is, natural circulation of cooling air along an open circuit through the reactor vessel to remove decay heat into the atmosphere in the emergency cooldown mode. The BREST OD-300’s ECCS consists of four independent cooling channels or heat removal channels. A flow diagram of one of the cooling channels is presented in Fig. 2 (Adamov et al. 2019). The ECCS comprises the following components

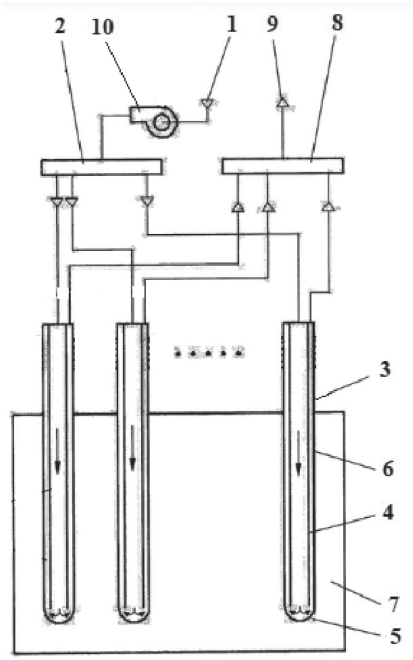

Figure 2. ECCS flow diagram.

and sections: an air intake section, distribution manifolds, inlet and outlet pipelines, Field-type heat exchangers, return manifolds, control valve assemblies, and a draft pipe.

The cooling air moves as follows: atmospheric air with seasonal temperature and ambient humidity enters through the air intake 1 and then through the dust filters. Downstream of the filters, the air flows through pipelines into four distribution manifolds 2, each of which is connected to 12 primary circuit heat exchangers or Field tubes 3 (11 main heat exchangers and 1 information channel heat exchanger). When in the heat exchangers, the air enters the downcomer 4, is heated partially, and then enters the annular section 5 where, while moving upwards, it is heated from the outer side of the Field tube 6 taking thermal energy from the coolant 7. Heated air from 11 Field heat exchangers enters the return manifold 8, with one of the Field heat exchangers acting as an information channel to control the output power. Leaving each of the manifolds, the heated air moves through an individual pipeline to enter the master gate valve assembly and enters then the fixed stacks 9 while creating thrust. As designed, with the lead temperature outside the heat exchange tube being 600 °C and with natural air circulation, the Field heat exchanger design (no external pipe fins) provides for the unit heat removal capacity of one ECCS channel being at a level of up to 2.0 MW. The estimates were based on a mass cooling air flow rate of about 10 kg/sec and an air velocity in the Field heat exchanger of 2 to 3 m/s (with the maximum air velocity in the system, permissible in terms of strength, being up to 50 m/s). Therefore, one Field-type heat exchanger for the BREST OD-300 conditions has a thermal power of about 160 kW. At the same time, there is a dependence of the cooling air natural circulation parameters on external conditions, which can lead to instability in the ECCS operation. In conditions of a beyond design basis accident caused by the crash of a large aircraft, the stack can be damaged, which will complicate the ECCS operation based on natural circulation. A small thermal power of a single ECCS Field heat exchanger dictates the need for a large number of such heat exchangers to be installed on the reactor lid. Taking into account the limited space (along the radius on the reactor periphery), it appears to be rather difficult to scale up this ECCS design for a larger reactor (BR-1200). In the BR-1200 reactor, there is four times more decay heat than in the BREST OD-300, and the ECCS is expected to remove at least 28 MW of thermal power. Therefore, the required thermal power of the ECCS can be achieved by using up to 170 Field-type heat exchangers of the type. It is rather difficult to install such a number of heat exchangers within the BR-1200 reactor vessel and on the reactor lid. The need for increasing the ECCS thermal power is critical in terms of scaling up this design so that to make it fit for the BR-1200 reactor to reduce the system dimensions, total steel content and cost, including the cost of developing and justifying the new design in the event it is not possible to employ the ECCS technical solutions justified as part of the BREST OD-300 design. The thermal power of the BREST OD-300 ECCS to be achieved is defined by the mass flow rate of cooling air through the ECCS heat exchangers in the natural circulation mode. Increasing the ECCS thermal power to be removed from the reactor facility in emergencies requires increasing the rate of the cooling air circulation through the system while ensuring the overall passive status of the system. An increase in the rate of the cooling air circulation through the ECCS heat exchangers can be achieved by using forced circulation instead of natural circulation. To meet regulatory requirements for passive systems, an upgraded ECCS design is proposed, in which forced circulation of air in an emergency cooling mode is provided by the operation of standard fans (item 10 in Fig. 2) installed on the air intake line in each channel of the BREST OD-300 ECCS under deign. To generate the energy required for the fan operation, each Field heat exchanger can be equipped with a thermoelectric generator (TEG, see Fig. 3) to be installed along the section submerged in the lead coolant to convert the internal thermal energy of the cooled down reactor into electrical energy for powering the fan that pumps cooling air in the forced circulation mode (Zaryugin et al. 2017).

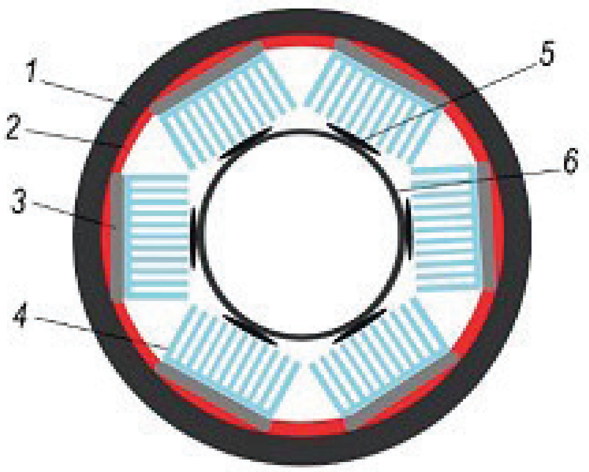

Figure 3. Diagram of the Field heat exchanger with a TEG (cross-section).

The operation of the heat exchanger with a Field tube and a TEG is as follows. Cold air is forced by a fan into the Field heat exchanger through the distribution manifold and pumped then through the internal Field tube 6. In the space between the downcomer and the riser, a TEG is installed, which consists of six sealed thermoelectric batteries (TEBs) 3 pressed by disc springs 5 to the heat sink 2. Ribbed radiators 4 are installed on the TEB inside, which also act as stiffeners for spacing the downcomer and increasing the surface of heat exchange with air. The expected electric power of one TEG is not less than 150 W. To effectively increase the thermal power of one emergency cooling channel comprising 12 Field tubes, the calculated fan power shall be about 1 kW. In the proposed system, the total expected electric power of the heat exchangers in one channel will be not less than 1.65 kW. Therefore, estimates show that it is possible to increase the thermal power of one ECCS channel to 3 to

3.5 MW by using forced circulation of cooling air instead of natural circulation while preserving the general principle of the ECCS passivity. The system will start to operate automatically when the coolant temperature increases and there is a temperature drop through the TEG. A temperature drop means that electricity is generated and the fans start to operate for the cooling air circulation. At the same time, it is possible to avoid using information channels, which, in the course of normal operation, release continually into the atmosphere up to 0.5 MW of heat.

Passive system for the VVER (PWR) in-vessel core melt retention

To reduce the radiological consequences of an SBDBA involving core melting, current NPP designs include devices for management of severe accidents developed and introduced to protect and mitigate the release of fission products to beyond the containment. In case of an SBDBA, current VVER (PWR) NPP designs take into account the potentiality of core melting, reactor vessel melt-through and corium (core melt) escape into the subpile space. The escape of corium to beyond the reactor vessel boundaries leads to it entering the reactor vault and interacting with the vault concrete with a large amount of generated hydrogen, the concrete base damaged, and the corium entering the soil and fission products propagating in an uncontrolled manner to beyond the containment limits. The accident response costs in this case are expected to exceed greatly the cost of the NPP as such. A similar accident occurred at the Fukushima Daiichi plant in Japan. A concept has been implemented for the medium thermal power reactor SBDBA management with corium confined within the reactor vessel, the vessel's outer surface being passively cooled with water and a sub-cooled boiling mode provided in conditions of natural cooling water circulation. For corium confinement, the reactor vault is filled with cooling water (water is supplied before corium starts to get onto the reactor bottom) which passively cools the reactor vessel's outer surface in a subcooled boiling mode with natural circulation, removal of generated steam, its condensation on the containment's inside, and the condensate getting back closing so the circulation loop. This solution is not applicable to larger reactors (of over 3000 MW(th) or 1000 MW(e)) because of more decay heat. With high heat fluxes (with a heat flux density of over 1.2 to 1.4 MW/m^2 depending on the inclination angle of the boiling surface) caused by much decay heat, a departure from nuclear boiling takes place on the vessel's outer surface as the result of the coolant nucleate boiling that passes into film boiling. The departure from nucleate boiling is accompanied by an abrupt deterioration of heat transfer, an increase in the vessel temperature up to the melting point, and the reactor core melting with corium escape to beyond the vessel. For this reason, current designs of large tank-type reactors use a concept with external core melt confinement using an external corium localization device, known as the molten core catcher (MCC) installed in the subpile space, as the localizing safety system in the event of an SBDBA. However, the use of this device leads to an increase in the power unit construction capital costs and time. The major reason behind the limited thermal power of the melt confinement system is a small cooling water flow rate in conditions of natural circulation, as defined by general requirements for ensuring passive operation of the system. Research has been under way worldwide to develop different technical solutions to increase the thermal power of in-vessel core melt retention systems:

- creation of microporous coatings on the reactor vessel surface; this solution is ineffective since the micropores become contaminated in the course of the reactor accident-free operation for 60 years or more, as well as in the event of the cooling water boiling on the surface;
- creation of shaped channels for the cooling water flow around the reactor vessel, this leading to a minor increase in the coolant flow at a given vessel point with the maximum heat flux; in this case, it is necessary to know exactly the distribution of the heat flux on the reactor vessel surface, and current models provide only an approximate estimate;
- drip irrigation of the reactor vessel with the use of sprayers, which leads to an increase in the critical heat flux density, but creating pressure in the sprayers requires that there are active components of the system (energy source, control signal, pump).

To increase the thermal power of the corium confinement system, it is necessary to increase the pumping rate for the cooling water flowing over the reactor vessel. The critical heat flux and the coefficient of heat transfer from the vessel to the cooling water increase as the mass velocity of the two-phase flow grows. This requires forced circulation of cooling water to be used instead of natural circulation. To generate the required energy for the forced circulation of cooling water, the reactor vessel can be equipped with thermoelectric batteries to convert the thermal energy removed from the reactor vessel to electrical energy for powering the pump that transfers cooling water in the forced circulation mode. Given the operating peculiarities of the proposed solution, it is possible to design a corium confinement system in the form of two circuitry solutions (Zaryugin et al. 2018):

- with an open coolant circulation circuit with boiling on the reactor vessel and steam condensation on the containment, similar to the corium confinement concept for NPP designs with small and medium tank-type reactor facilities; this circuitry solution is promising for effective VVER (PWR) NPPs not equipped with a core catcher but requires much cooling water;

- in the form of a closed circulation circuit through a cooling jacket around the reactor vessel with the final heat disposal into the environment through the SG PHRS heat exchanger.

Preliminary calculations show that a thermoelectric generator is capable to generate not less than 40 kW of electric power under these conditions, which is quite enough to power the pumps that supply cooling water to the reactor vessel. The thermoelectric generator installation diagram is shown in Fig. 4.

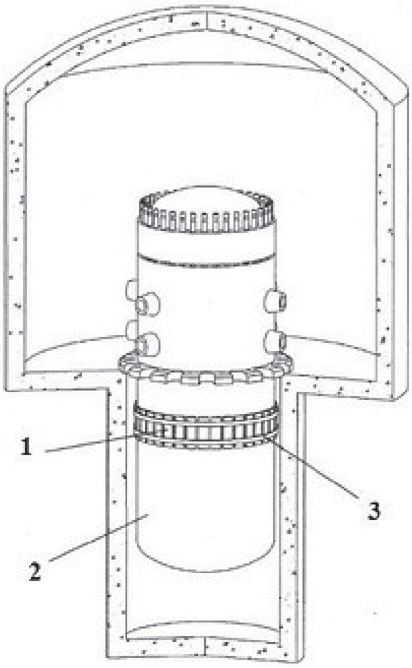

Figure 4. Installation of a thermoelectric generator.

As shown in Fig. 4, the thermoelectric generator has the form of a thermoelectric battery belt 1 installed on the reactor vessel's outer surface 2. To ensure the reliable position and contact with the surface, the thermoelectric batteries are tightened with hoops 3. The thermoelectric generator is installed above the corium level where the heat flux through the wall is defined by radiation from the corium surface. This area will have the smallest heat flux. Thermoelectric batteries are flown over by cooling water.

Conclusions

In accordance with the IAEA classification (IAEA-TECDOC-626 1991), the passive safety systems described above fall under category C and have the following characteristics: no control signal, no external power sources or forces, mechanically moving parts regardless of whether there are working fluids or not. In accordance with NP-001-15 2015 "A safety system shall perform the specified functions in case of any initiating event that requires its operation and in case of failure of any one of the active or passive components having mechanically moving parts independent of the initiating event." To satisfy this requirement of the GSR (General Safety Regulations), redundancy needs to be provided for the hydraulic machine for moving the working fluid or gas. The generated electricity can also be used as an additional source of reliable power supply for measuring tools and other equipment in emergency modes other than involving operation of the NPP standard systems, including the generator. Implementing the proposed technical solutions requires R&D to be undertaken, including for justifying the service life of thermoelectric converters in conditions of radioactive emission.

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