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ANALYSIS OF ACCIDENTS OF THE WWER-1000 REACTOR IN WHICH EMERGENCY COOLING HEAT EXCHANGERS OPERATE

The object of research is the emergency operation modes of the WWER-1000 nuclear installation elements, which also use emergency cooling heat exchangers. The analytical studies carried out are based on an analysis of the operating documentation of the above-mentioned nuclear installation. An analysis of the elements of the emergency core cooling system, which includes emergency cooling heat exchangers, has been carried out. This analysis has shown that in order to localize the accidents of the WWER-1000 reactor unit, the coolant that comes out of the leak is collected in the tank of the plant and from there is pumped by pumps through the above-mentioned heat exchangers. This ensures that the heat of the coolant escaping from the leak is removed and the reactor core is effectively cooled using already cooled water.

As a result of a comparative analysis of design accidents at the WWER-1000 reactor unit, it has been established that the emergency core cooling system is involved in accidents related to a rupture of the first and second reactor circuit pipelines within the containment. Such accidents include small, medium and large leaks in the primary circuit as well as ruptures in the steam line or feed water pipeline of the steam generator (within the containment). A detailed review of the parameters of the coolant that flows out of the leak and into the tip-tank shows that the most conservative accident involving emergency cooling heat exchangers is a «Large leak mode. Bilateral rupture of the main circulation pipeline DN 850 mm». In this accident, the temperature of the coolant in the tip-tanks reaches 110 °C and subsequently enters the inter-tube space of the heat exchangers.

Currently, there is an urgent task to justify the safe operation of nuclear power plant equipment and emergency cooling heat exchangers in particular. The results of the research can serve as baseline data for determining the thermal stress state of the above-mentioned heat exchangers in accidents of the WWER-1000 nuclear installation.

Keywords: emergency cooling heat exchanger, lifetime extension, safe operation, accident, emergency core cooling system.

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1. Introduction

Nuclear energy is an important component of the fuel and energy complex of various countries of the world and Ukraine in particular. Technical condition assessment of elements of nuclear power plants (NPPs), and their safe operation is a priority for nuclear power regulators and organizations that operate it. Much attention is paid to these issues:

- in research and analytical works [1, 2];
- in normative documents [3–5].

In Ukraine, the majority of nuclear power plants operate WWER-1000 nuclear installations (NI), which include a large number of equipment and other elements. One of the main elements of the WWER-1000 are emergency cooldown heat exchangers (ECHE heat exchanger) 08.8111.335 SB, which are part of the emergency core cooling system (ECCS system). ECHE Heat exchangers takes an important role in the localization of accidents of the NI, since they allow efficient cooling of the core. Proceeding from the fact that ECCS system is an important system for NPP safety and takes a key role in the

localization of NI accidents, a lot of research has been devoted to the analysis of this system, which is part of not only the WWER-1000 NI, but also other reactors. An example of such research is works [6–8], which consider the operation of ECCS system as part of WWER-440, WWER-1000 and CANDU reactors. Currently, work is being actively carried out to lifetime extension of Ukrainian NPPs units, and therefore there is an urgent task in justifying the safe operation of NPP equipment, and ECHE heat exchangers in particular. This statement is due to the fact that the justification of the safe operation of equipment that operates under normal and accidents is one of the requirements for lifetime extension of an NPP [9, 10]. In this regard, *the object of research* is the operating modes of WWER-1000 NI elements in accidents in which ECHE heat exchangers are involved. This will make it possible to determine the most conservative mode of operation of these heat exchangers for further justification of their safe operation during accidents. *The aim of research* is to analyze the parameters of the coolant flowing in the ECHE heat exchangers, which correspond to various accidents of the WWER-1000 NI.

2. Methods of research

To achieve the set aim of research, an analysis of the operational documentation of the WWER-1000 NI was performed. This documentation contains information about the values of the fluid parameters that flowing in the equipment and pipelines of the primary circuit of the NI. In addition, the nature of the occurrence of accidents, the values of the parameters of the environments, methods of localizing accidents and the possibility of the coolant that flows out of the leak into the boron storage tank was analyzed.

As a result of the analysis, a conclusion was made about the most conservative accident, in the localization of which the ECHE heat exchangers are involved.

3. Research results and discussion

In accordance with the operating instructions for ECCS system [11], it was established that this system consists of a low pressure ECCS system (ECCS LP) and a high pressure ECCS system (ECCS HP). Systems ECCS LP and ECCS HP, in turn, consist of three independent channels, each of which includes:

- ECHE heat exchangers TQ10(20,30)W01 (items 4, 5, 6 Fig. 1);
- pumps TQ12(22,32)D01 (items 7, 10, 12 Fig. 1) or TQ13(23,33)D01 (items 8, 9, 11 Fig. 1);
- control valves, pipelines, electrically conductive and manual fittings, measuring instruments, emergency reserve tank of boron TQ10(20,30)B01 (pit-tank) (positions 1, 2, 3, Fig. 1), which is common for all 3 channels. The ECCS system is designed for:
 - emergency cooling of the reactor core and then continuous removal of residual heat from it in case of accidents associated with decompression of the primary circuit;
 - scheduled cooling of the primary circuit during RP shutdown for scheduled preventive maintenance and for removal of residual heat during core refueling;
 - removal of residual heat from the core during repair work on the equipment of the reactor plant with a decrease in the coolant level in the reactor to the axis of the cold loop nozzle without unloading the core.

A schematic diagram of the ECCS is shown in Fig. 1, where 13 – steam generators (SG), 14 – main circulation pumps (MCP), 15 – hydraulic tanks of ECCS (HT ECCS).

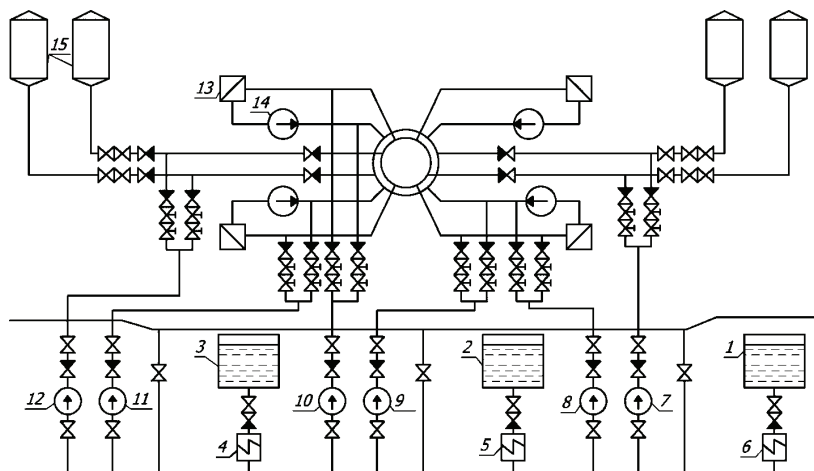


Fig. 1. Schematic diagram of the Emergency Cooling Core System

As can be seen from the ECCS system schematic diagram, the coolant enters the ECHE heat exchangers directly from the pit-tanks. In this case, in case of NI accidents associated with pipeline rupture, part of the hot coolant will enter the pit-tanks and will continue to flow through ECHE heat exchangers to the suction of the ECCS LP or ECCS HP system pumps for further cooling of the core. Let's observe an increase in the temperature of the coolant, which is pumped through the heat exchangers.

As a result of the analysis of the operational documentation [12], it was established that ECCS system is involved in accidents of the NI associated with the rupture of the pipelines of the first and second circuits within the containment scope. This analysis was carried out using the recommendations given in the documents [13–15].

Accidents of NI, in which ECHE heat exchangers are involved include:

1. Small leaks of the primary coolant (equivalent leak diameter up to 50 mm): rupture of the drainage pipeline Du32.
2. Average leaks of the primary coolant (equivalent leak diameter 50–200 mm):
 - rupture of the ECCS HP system pipeline;
 - rupture of the pipeline of the purge-make-up system;
 - opening of pulse-safety devices of the pressure compensator (PSD PC);
3. Large leaks of the primary coolant (equivalent leak diameter over 200 mm):
 - bilateral rupture of the main circulation pipeline (MCP) DN 850 mm;
 - rupture of the connecting pipeline PC;
 - rupture of the connecting pipeline HT ECCS;
 - rupture of the injection pipeline PC;
 - rupture of the connecting pipeline PSD PC.
4. Rupture of steam pipelines of SG within the containment.
5. Rupture of the SG feed water pipeline within the containment.

The aforementioned accidents are included in the design basis accidents category corresponding to the categories accepted in international practice [13].

Among the accidents with loss of primary coolant, the worst in terms of temperature and pressure rise in the containment is the instantaneous bilateral rupture of the MCP pipeline DN 850 mm. The largest increase in the parameters in the containment (temperature and pressure), which arise during a given leak, is characteristic for the ruptures of the hot nick of the MCP pipeline.

Let's consider the course of the accident «Large leak mode. Bilateral rupture of the main circulation pipeline DN 850 mm»:

- during the first and approximately 25–30 seconds, there is a rapid increase in pressure and temperature in the rooms of the containment. This is due to the intense release of steam and water from the MCP pipeline. At the same time, the vapor content in the air of the containment increases, especially in rooms adjacent to a room with a leak source. By the time it reaches its maximum value, the pressure in various rooms of the containment is practically equalized;

- at the 62th second of the process, the ECCS HP and ECCS LP systems start to work, while the ECCS LP pump takes water from the pit-tanks, and therefore there is a slight decrease in the mass of water in the tanks (Fig. 2);
- at 73th second of the process, water is injected into the containment chamber through the nozzles of the sprinkler system. In connection with the inclusion in the operation of the sprinkler system, the overflow of hot water into the tip-tanks increases and a further increase of its temperature is observed (Fig. 3). After a while, the water temperature decreases due to the continued operation of the sprinkler system and the ECCS LP system, as well as due to a decrease in the temperature of the condensate coming from the upper rooms of the containment and heat removal to the steam-air mixture;
- at 80–90 seconds of the process, the overflow of water from the GA306/1-3 rooms premise into the tip-tanks begins (when the level of the flange of the drain hole is 15 cm), that is, the circulation loop is closed. After that, the mass of water in the tip-tanks begins to grow. The inflow of a large mass of hot water after the circulation loop is closed also leads to an increase in the water temperature in the tank;
- at the 278th second of the process, the ECCS HP pump switches to work from the tip-tanks, while the

water intake increases. In this regard, a repeated decrease in the mass of water in the tanks is observed until the core is filled with water. Starting from 1400 seconds, stable water circulation is established without significant fluctuations in the mass (level) of water in the pit-tanks;

- at 3600th second, the pressure in the containment rooms reaches a value of about 30 % of its maximum value. The operation of the three ECCS systems channels, and ECHE heat exchangers, compensates for the loss of the primary coolant and provides heat removal from the reactor core.

The above values of the water parameters in the pit-tanks are given in the document [12]. These parameters were obtained using the DYN-3D software, which is designed for calculating both stationary and non-stationary (emergency) modes of operation of the WWER-1000 NI. Information about this calculation code is described in documents [16, 17]. For more accurate modeling of heat and mass transfer processes to the elements of the containment, thermal structures are used in the data set of computational models. The distance between the temperature nodes of the structures is calculated in accordance with the recommendations [18, 19], which makes it possible to accurately reflect the processes of heat transfer and condensation.

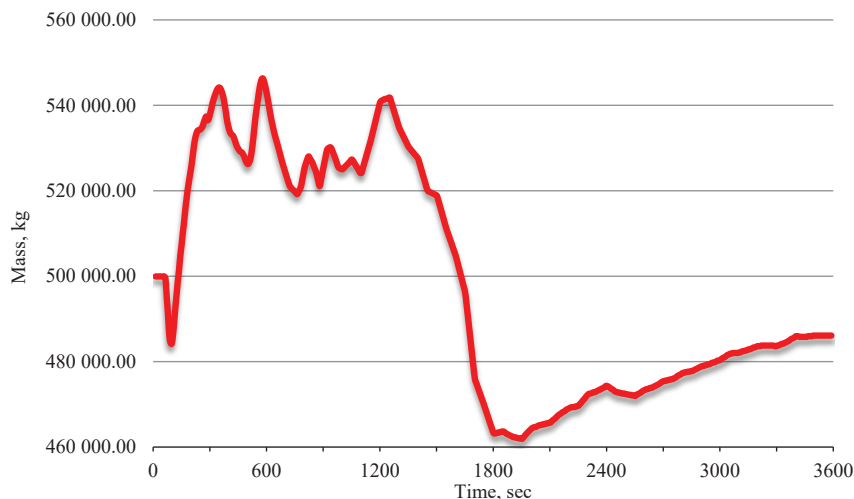


Fig. 2. Weight of water in pit-tanks

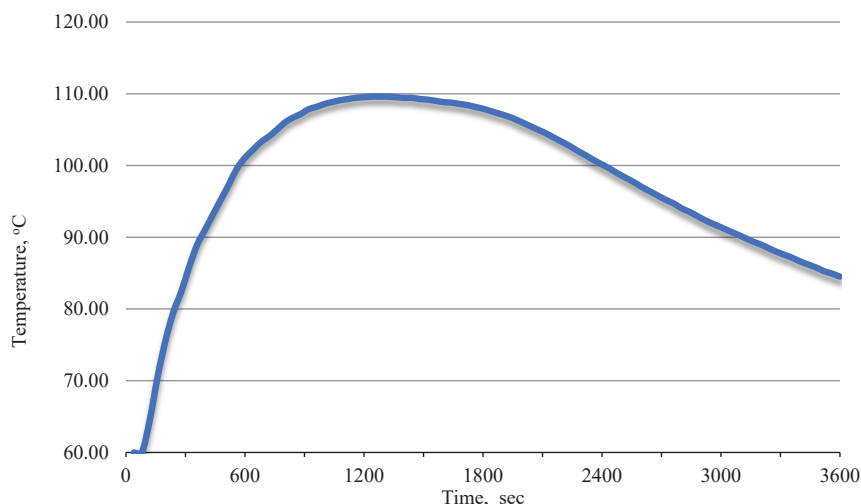


Fig. 3. Temperature of coolant in ECHE heat exchanger

Consider accidents that are characterized by a rupture of the secondary circuit pipelines, and for the localization of which ECHE heat exchangers are used. Among those that most affect the rise in the water temperature in the tip-tanks, and, accordingly, the coolant in the ECHE heat exchanger, are: «Rupture of steam pipelines of SG within the containment» and «Rupture of the SG feed water pipeline within the containment» accidents. These emergencies are similar. The only difference is the time of the emergency stages and the conditions under which they are localized.

Consider the course of the aforementioned accidents:

- as a result of the rupture of the steam-line or the feed water pipeline, an intensive outflow of the coolant into the containment room occurs. The release of the coolant from the secondary circuit pipelines leads to an increase of the temperature and pressure in the containment;
- approximately during the first 103 seconds (for accident «Rupture of steam pipelines of SG within the containment») and 4 minutes (for accident «Rupture of the SG feed water pipeline within the containment») there is a rapid increase of pressure and temperature in the containment rooms. This is due to the intense release of steam and water with high temperature and pressure from the pipelines of the secondary circuit. At the same time, the vapor content in the air of the containment increases, especially in rooms that are adjacent to a room with a leak source. By the time it reaches its maximum value, the pressure in different rooms of the containment volume is practically equalized;
- at the 66th second (for accident «Rupture of steam pipelines of SG within the containment») and at 78th second (for accident «Rupture of the SG feed water pipeline within the containment»), water is injected into the pressurized volume through the nozzles of the sprinkler system. At the same time, a decrease in the mass of water in the tip-tanks is observed;
- after the end of the first 2 minutes of the accident «Rupture of steam pipelines of SG within the

containment» there is a decrease in the parameters of the temperature and pressure in the containment. This is due to a decrease in the release of the leak mass into the containment due to the closure of high-speed shut-off valves of non-emergency circuits. In addition, steam condensation and heat removal by concrete and metal structures, as well as equipment – so-called thermal structures, affect the process of pressure reduction in the containment rooms;

- after the end of the first 4 minutes of the accident «Rupture of the SG feed water pipeline within the containment», the parameters of the temperature and pressure in the containment are reduced. This is due to a decrease in the release of the leak mass into the containment due to the cessation of the feed water supply, caused by the closure of the valves on the main feed water pipelines at the ECCS signal;
- at the 13th minute (for the accident «Rupture of steam pipelines of SG within the containment») and at the 10th minute (for the accident «Rupture of the SG feed water pipeline within the containment»), water overflow from the GA306/1-3 rooms premises into the tip-tanks starts, that is, the circulation loop is closed. This is due to the fact that the water level in the GA306/1-3 rooms has reached a height of 15 cm and the water overflows over the side into the tip-tanks. After the circulation loop is closed, the water temperature in the tip-tanks begins to rise, due to the overflow of a large mass of hot condensate (Fig. 4);
- at the 1000th second, the pressure in the containment rooms reaches about 50 % of its maximum value and the accident is localized.

Based on the above, it can be concluded that the highest values of the coolant temperature at the inlet to the ECHE heat exchanger correspond to accident «Large leak mode. Bilateral rupture of the main circulation pipeline DN 850 mm». This accident should be further considered as the most conservative of design basis accidents, in which ECHE heat exchangers are involved, to justify their safe operation during accidents of the WWER-1000.

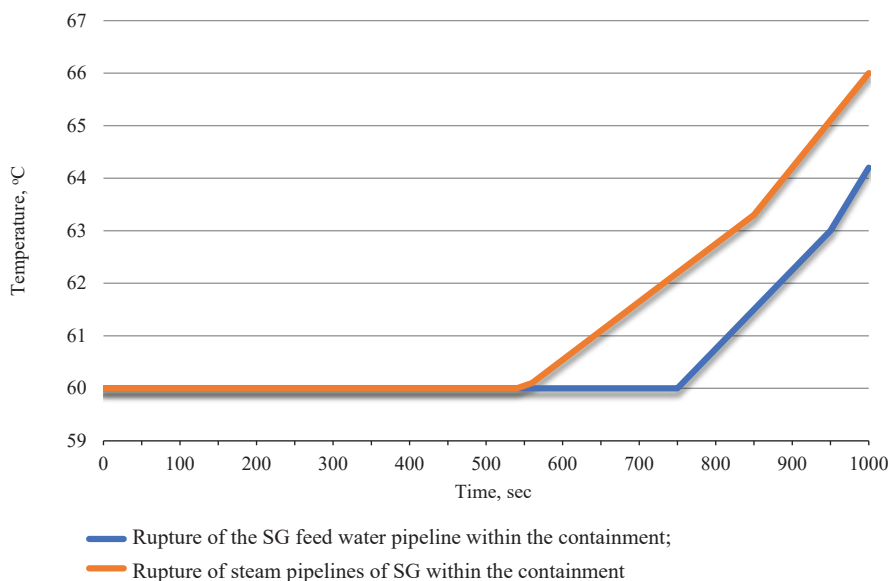


Fig. 4. Temperature of coolant in ECHE heat exchanger of accidents

4. Conclusions

The research analyzed in detail the accidents of the WWER-1000 NI, in the localization of which ECHE heat exchangers are involved. Information about the accidents is contained in the document [12], the analysis results of which give the following conclusions:

1) ECCS system, which include ECHE heat exchangers, participates in nuclear installation accidents associated with rupture of pipelines of the first and second circuits within the containment;

2) among the accidents with leak of coolant from the pipelines of the primary and secondary circuits, the worst in terms of temperature and pressure growth in the containment is the accident «Large leak mode. Bilateral rupture of the main circulation pipeline DN 850 mm».

As a result of this research, it can be concluded that there is an urgent task to justify the safe operation of ECHE heat exchangers during accidents of the WWER-1000 NI, the basis for which can be the results of this work.

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