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AN AUTONOMOUS SYSTEM OF A SPENT FUEL POOL COOLING IN WWER-1000

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The issue of WWER-1000 spent fuel pool cooling in total blackout conditions is evaluated. A model of a spent fuel pool for MELCOR computer code is developed. Basic information about a spent fuel pool construction is shown. Basic data for a spent fuel pool cooling system calculations are given. A scheme of a spent fuel pool autonomous cooling system as well as calculation results of its operation are provided. The analysis results of of the autonomous cooling system operation is performed. The calculation of the autonomous cooling system equipment is done. Necessary network parameters are defined. The approximate cost of the cooling system is determined.

INTRODUCTION

Loss of cooling water of spent fuel pool in a total blackout was caused by uncontrolled temperature rising in the spent fuel pool of the Fukushima nuclear power plant during the course of a severe accident, that happened on March 11, 2011. Another cooling system of spent fuel pool was not provided.

The relevance of the loss of cooling water of spent fuel pool problem underlines by statement that was made on March 25, 2011 Council of the European Union's about re-evaluation of safety of European nuclear power plants on the basis of a comprehensive, open risk assessment (“stress tests”). At its fifth meeting to review the implementation of commitments under the Convention on Nuclear Safety (4–14 April 2011), Member countries of the Convention, “Fukushima-Daiichi” a joint statement on the accident at the plant indicated the need for a reassessment of nuclear safety and the immediate implementation of additional measures to improve NPP safety.

FORMULATION OF THE PROBLEM

The objectives of this research are the development and modeling of autonomous water cooling system cooling the spent fuel pool at the failure of the primary cooling system, as well as determining the time in which such a system must be put into operation in order to prevent boiling of water in the spent fuel pool. It is also necessary to take into account the most conservative version of the emergency unloading from the active zone, when the power of energy release from fuel assemblies are maximized.

To success in the research necessary to develop a computational model of the spent fuel pool and the autonomous cooling system, to determine the time before the start of boiling water in the cooling pool, as well as the minimum necessary to determine the parameters under which will operate the emergency cooling system. The analysis used a conservative assumption that the fuel assemblies are unloaded from the active zone in the spent fuel pool after 13 days after reactor shutdown (the minimum time necessary to disassemble the reactor for unload fuel rods).

INITIAL CONDITIONS OF CALCULATIONS

The construction of the spent fuel pool is taken identical with spent fuel pool on the unit No 3 SUNPP with WWER-1000. The spent fuel pool consists of 4 sections: three cassette compartment with shelves packed fuel assemblies constructed specifically for the storage of spent fuel assembles and to install airtight containers, and one that is a universal socket. Universal socket can be used to install the cover with fresh fuel assemblies. The division into three cassette compartment allows you to carry out repair work in one compartment, while fuel assemblies are placed in the other two. Capacity of spent fuel pool is – 563 cells for fuel assemblies and 50 cells under the shipping cask.

Calculating the most conservative version of accident because of high level of power ratio, assume that the emergency uploading of active zone is done in the cassette compartment number 3, that accommodates 110 fuel assemblies.

Initial data:

- the water temperature in the spent fuel pool – 50 °C;
- initial water level – 8.03 m;
- the total thermal power of fuel assemblies: Compartment 1 = 1638.2 kW, Compartment 2 = 1492.2 kW, Compartment 3 = 2151.3 kW;
- the total thermal power of fuel assemblies in an emergency active zone unloading: Compartment 3 = 5689.2 kW.
- temperature at which the autonomous cooling system starts to work – 90 °C.

The volume of water, defined in the cassette compartment, is calculated including the volume of water displaced by spent fuel racks, fuel assembles, etc. When calculating the volume of water displaced following assumptions were made:

1) the amount of fuel assemblies, protective covers in the shelves, and the failed fuel detection system was calculated according to their geometrical dimensions;

2) was taken into the account in each compartment 2 spacer plates of 5 cm and a thickness of the base plate 6 cm;

3) when calculating the volume of the plates is taken into account with a gap between the sections and sealed shelving section with shipping casks (accepted model 20 cm) and perforation depending on the number of fuel assemblies;

4) the volume of slats attached to the edges of covers for a spacing between the covers, taken equal to the

volume of the two plates (compartment area 20 mm thick) in the top and bottom covers.

THE NODALIZATION SCHEME OF THE SPENT FUEL POOL

The behavior of the spent fuel pool is determined by modeling his constructions, cooling water, the residual energy of spent nuclear fuel by means of Account Code MELCOR 1.8.5 [1].

The nodalization cheme of the spent fuel pool is shown on the Fig 1. In this model spent fuel pool represented by 22 control volumes, connected by 25 ways of flowing.

Control volumes CV476, 477, 478 are modeling the lower part of the compartments of the spent fuel pool – the volume of water between the floor and the bottom baseplate. CV486, 487, and 488 are part of the compartment, where the racks are located directly, shipping casks, support and spacer plate. Directly in the modeled data volume capacity of the residual energy in the form of fuel assemblies internal energy source via packet control functions. Thus, according to the initial conditions for the CV486 control function CF824 is given the power of the internal power source, which is equal to 2151.3 kW for CV487 – CF814 equal to 1492.2 kW and CV488 – CF804 equal to 1638.2 kW.

Modelling of the upper volume CV493 allows to consider the overflow of water from section N 1 to section N 2 during thermal expansion of the water when the water level in the spent fuel pool is in the storage mode. The possible overflow of water from the section N 3 is modeling using FL315.

For including the hydrostatic pressure gradient and the simulation of natural circulation processes in the spent fuel pool upper part is divided into four height control volume CV493, 494, 495, 496 for compartments No 1, 2, and CV489, 490, 491, 492 – For compartment No 3.

When modeling of flow paths taken into account the process of interfacial interaction, for this purpose in each flow path was set interfacial friction factor of 0.01. Ways of flowing FL314 and FL313 are modeling the connection between the spent fuel pool and the containment. With the ability to FL316 simulated water overflow as a result of thermal expansion of water at a level the spent fuel pool in overload mode.

Because of minor influence in the spent fuel pool model conservatively, not simulated heat transfer from the water to the spent fuel pool walls.

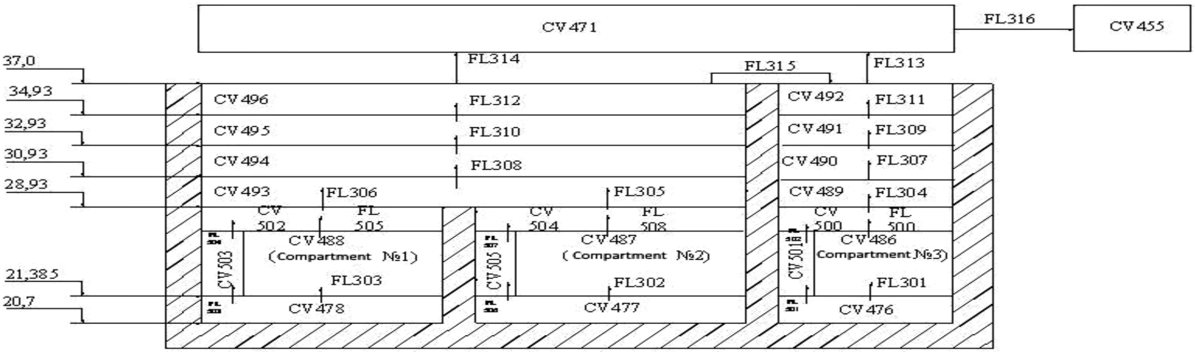

Fig. 1. The nodalization scheme of the spent fuel pool

AN AUTONOMOUS SYSTEM OF A SPENT FUEL POOL COOLING

The spent fuel pool stationary is cooled by cooling system which consists of three channels, each of them includes a pump and heat exchanger. One of them always active. The cooling water that circulates in the space of the tubular heat exchangers is pumped by separate pumps. Consequently, the power loss affects the efficiency of the system, disabling not only the cooling water storage pool pump system, but also makes it impossible pumped cooling medium pumps. The parameters of the system are regulated according to the current water temperature in the spent fuel pool.

In an emergency, it proposed to activate the autonomous system of a spent fuel pool cooling. The scheme of the autonomous system of a spent fuel pool cooling is shown in Fig. 2. The scheme is organized by 2 circuit. Inner loop stationary established inside the reactor building and if necessary connected by flexible hoses to a cell, the outer loop. A heat exchanger, pumps and generators are delivered to the diesel engines are provided with the compressed air cylinders and filled the spent fuel pool if part of the water before the cooling system connection evaporated.

In the nodalization scheme og the spent fuel pool the autonomous system working is realized by supplying water to the volume of CV476, 477, 478, which corresponds to pipelines supplying cooling water from pool cooling pumps. Water intake volume of organized CV500, 502, 504. Volumes CV501, 503, 505 are designed to improve the mixing of water in the compartments.

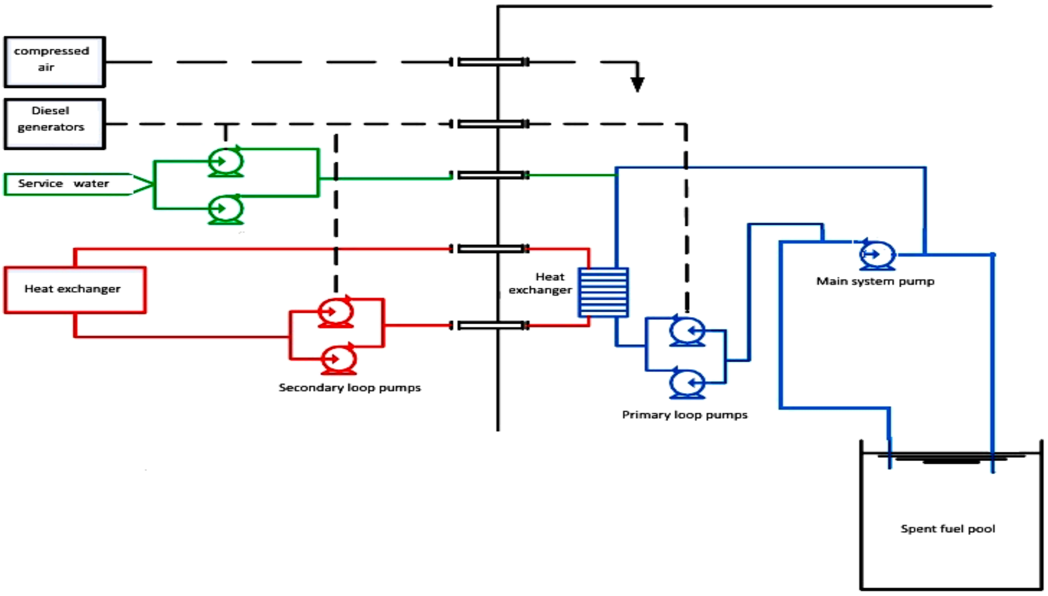

Fig. 2. The scheme of the autonomous system of a spent fuel pool cooling

THE RESULTS OF CALCULATION WHILE THE SPENT FUEL POOL COOLING IS ORGANIZED

The results of calculation are shown in pictures: for compartment 1 Figs. 3a, 3b, for compartment 2 in Figs. 4a, 4b, the compartment 3 in Figs. 5a, 5b, 5c. Pictures have a CVH designation, which means the compartment number in the nodalization scheme.

Analysis of the results of calculations show that the minimum required water flow in the autonomous cooling system equal to 50 m^3/h, for an emergency active zone unloading 80 m^3/h (see Fig. 5c).

The lowest temperature at which the boiling water in at least one of the compartments of the spent fuel pool was 65 °C, at this temperature begins boiling water in the compartment 3 (see Fig. 5b), as well as that at 60 °C water temperature in the compartment 3 is stabilized at a value less than the saturation temperature (see Fig. 5a). Regarding the compartments 1 and 3, the calculation results show that at a temperature of the cooling water of 60 °C a decrease in temperature of the water in these compartments (see Figs. 3a, 4a) and at a temperature of cooling water 65 °C is observed stabilization temperature of the water in these compartments (see Figs. 3b, 4b). When simulating an emergency active zone unloading 110 fuel assemblies in the third compartment of the minimum required value of the cooling water temperature is 40 °C (see Fig. 5c), and the observed stabilization of the temperature at a value less than the saturation temperature.

The cooling of the compartment 1 with temperature of cooling water 60 °C.

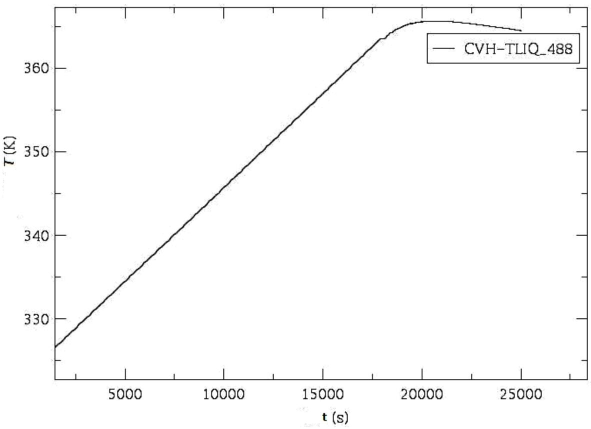

Fig. 3a. The line graph of the pool water temperature changes in the spent fuel pool in time

The cooling of the compartment 1 with temperature of cooling water 65 °C.

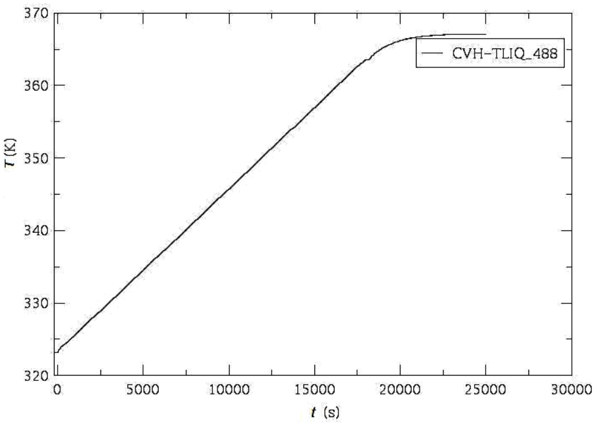

Fig. 3b. The line graph of the pool water temperature changes in the spent fuel pool in time

The cooling of the compartment 2 with temperature of cooling water 60 °C.

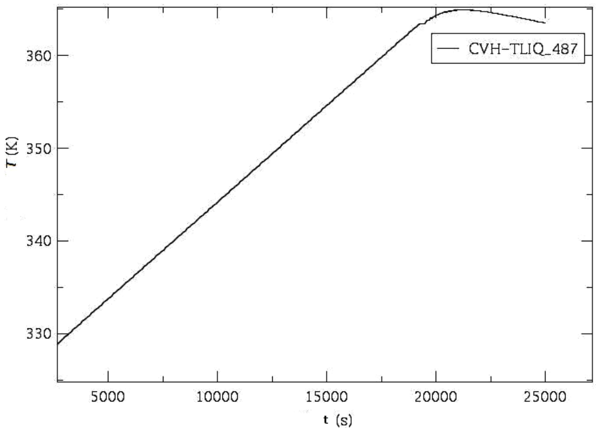

Fig. 4a. The line graph of the pool water temperature changes in the spent fuel pool in time

The cooling of the compartment 2 with temperature of cooling water 65 °C.

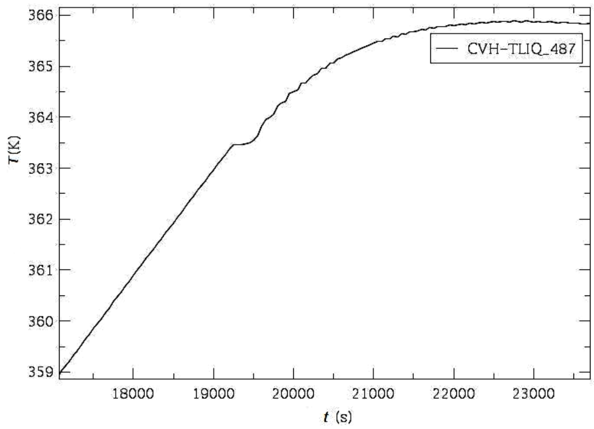

Fig. 4b. The line graph of the pool water temperature changes in the spent fuel pool in time

The cooling of the compartment 3 with temperature of cooling water 60 °C.

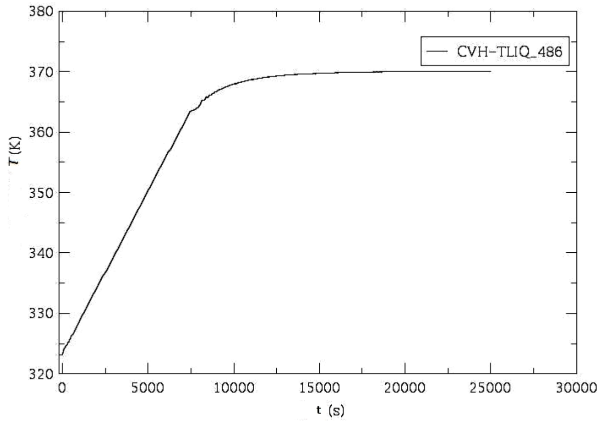

Fig. 5a. The line graph of the pool water temperature changes in the spent fuel pool in time

The cooling of the compartment 3 with temperature of cooling water 65 °C.

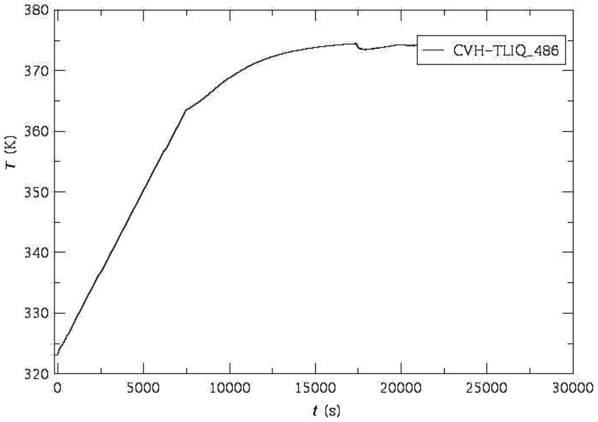

Fig. 5b. The line graph of the pool water temperature changes in the spent fuel pool in time

The cooling of the compartment 1 with temperature of cooling water 40 °C when 110 fuel assembles are uploaded into the compartment 3 after 13 days after reactor shutdown.

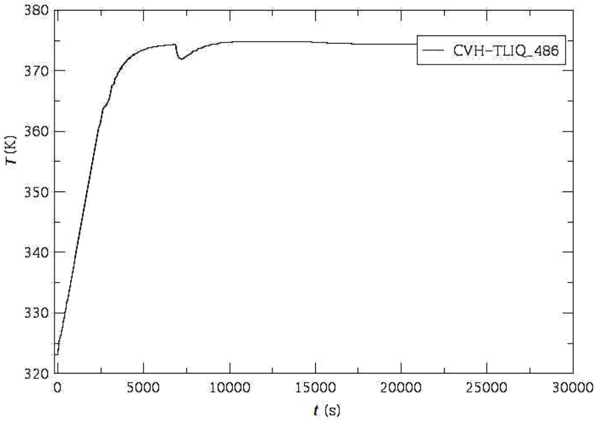

Fig. 5c. The line graph of the pool water temperature changes in the spent fuel pool in time

To realization the most conservative approach taken in the model of temperature in the compartments of achieving 90 °C as the start point of the cooling water in the compartments. The time to reach this temperature is shown in Table.

The time until the temperature in the spent fuel pool compartments 90 °C

No of compartment	The time until the temperature in the compartments 90 ^{0}C, s (h)	
1	1.78861E+04 (4.96)	
2	1.92257E+04 (5.34)	
3	7.45940E+03 (2.07)	2.60920E+03(0.72)*

*Time in emergency unloading bay 3110 fuel assemblies on the 13th day.

After the events at the Fukushima nuclear power plant began more intensive study of the cooling problems of the pools in total blackout. Various studies involve issues such as exposure of the fuel assembly with the boiling water, hydrogen evolution in the process of accidents, damage fuel assemblies, damage the floor of the spent fuel pool. Thus, in [2], including the results obtained present the result of the beginning of the boiling water in the spent fuel pool, which was

0.53 hours. Also in the “post-Fukushima” Development Research Center “Kurchatov Institute” simulated severe accident in the spent fuel pool during prolonged total blackout using account code SOCRATES. Simulated the following main processes for different valuesof the residual energy [3]:

- dynamics of heating and boiling water in the spent fuel pool;
- warm-up dynamics and the melting of spent nuclear fuel in the spent fuel pool;
- generation of hydrogen as a result of oxidation of the zirconium fuel assemblies and metal structures in the spent fuel pool.

For calculations is used a spent fuel pool the same with like in the unit N 1 of Balakovo NPP. The time for beginning boiling of water in this work is 0.68 hours.

Also, in [4, 5] a diagram and description of the passive fuel cooling system is shown. Implementing this system complicated by the fact that the newly laid pipeline communications, designed to transport water from the spent fuel pool can interfere with the movement of cargo handling machines; the distance between the shelves and the wall, where it is planned to place heat exchangers, is 675 mm at the bottom and 25 mm in the lateral parts. That may not be enough to accommodate the heat exchangers between the shelves and the walls of the spent fuel pool. It is necessary to take into account the requirements of not to low the boric acid concentration in the spent fuel pool in the case of depressurization of the coolant circulation circuit in the cooling system. And also do not forget about the ALARA principle, after conducting these works will lead to an increased dose loads on the personnel who would conduct them.

CALCULATION OF HEAT EXCHANGERS FOR THE SPENT FUEL POOL COOLING WATER SYSTEM

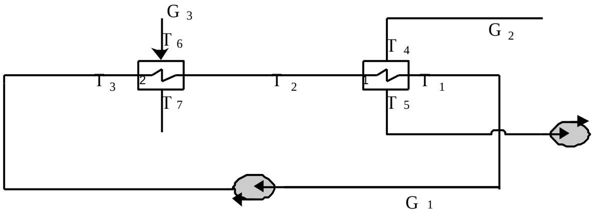

Fig. 6. The thermal schematic of cooling water system for the spent fuel pool

The thermal schematic of cooling water system for the spent fuel pool is shown in Fig. 6 – heat exchanger cooling water of the spent fuel pool. 2 – heat exchanger air-cooling water supplied to the spent fuel pool cooling water.

T_1 = 85 ºC – outlet temperature of cooling water; T_2 = 35 ºC – inlet temperature of the cooling water; T_3 = 85 ºC – inlet temperature to the heat exchanger 2; T_4 = 90 ºC – the temperature of the spent fuel pool cooling water; T_5 = 40 ºC – temperature of cooled water, which returns to the spent fuel pool; T_6 = 29.3 ºC – the air temperature supplied to the cooling heat exchanger 2; T_7 = 60 ºC – air temperature at the outlet of the heat exchanger 2; G_1 = 80 m^3/h – the rate of water flow in the cooling water circulation loop; G_2 = 80 m^3/h – the rate of the cooling water flow to the spent fuel pool; G_3 – air flow.

The temperature adopted in accordance with [6], as the highest average temperature in the Mykolaiv region.

The equation for the heat balance [7] of the heat exchanger 1 is

$$G_1 \cdot C_p \cdot (T_1 - T_2) = G_2 \cdot C_p \cdot (T_4 - T_5),$$

where Cp – specific heat of water.

Accept for the design of the system G1 = G2 = 22.2 kg/s.

Adopted for the heat exchanger 1 tube outer diameter D_o = 0.019 m tube wall thickness 0.001 m, the inner diameter Din = 0.017 m, water velocity in the tubes take w = 1.7 m/s.

Number of tubes in the tube bundle heat exchanger is equal to

$$n = \frac{G_1}{w \cdot f \cdot \rho} = 58,$$

where f – the cross section area of one of the tube, ρ – the density of water.

Because F_1 and F_2 are equal coefficients of heat transfer for the heat exchanger 1 are

$$\alpha_1^{'} = \alpha_2^{'} = Nu \frac{\lambda_1}{\mathrm{d_e}} = 12938.2 \frac{W}{m^2 \cdot K},$$

where of Nu – Nusselt number; $\mathrm{d_e}$ – equivalent diameter; λ_1 – water conductivity.

The heat transfer coefficient for the designed heater is

$$k = \frac{1}{\frac{d_{av}}{\alpha_1 \cdot \mathrm{d_{in}}} + \frac{\mathrm{d_{av}}}{2\pi \cdot \lambda_\mathrm{w}} \cdot \ln\left(\frac{\mathrm{d_{in}}}{\mathrm{d_o}}\right) + \frac{\mathrm{d_{av}}}{\alpha_2 \mathrm{d_o}}} = 6830.6 \frac{W}{m^2 \cdot K},$$

where d_{av} – average diameter tubes; λ_w – thermal conductivity of the wall material.

The average temperature difference in the heater determined by the formula

$$\Delta t = \frac{\Delta t_b + \Delta t_s}{2}, \quad \text{as} \quad \frac{\Delta \mathrm{t_b}}{\Delta \mathrm{t_s}} < 1.7,$$

where $\Delta t_b, \Delta t_s$ – a bigger and a smaller temperature difference (Fig. 7).

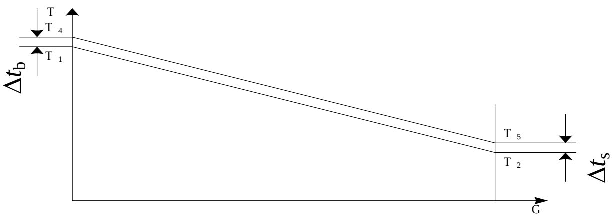

Fig. 7. The process of heating water in a countercurrent heater

The required heat transfer surface area of the heater is:

$$F = \frac{Q}{k \cdot \Delta t} = 135.8 \text{ m}^2.$$

The length of the tube bundle is

$$L = \frac{F}{\pi \cdot d_{av} \cdot n} = 41.4 \text{ m.}$$

With a length of tubing 3 m the number of turns is equal to

$$Z = \frac{L}{3} = 14.$$

Then the diameter of the envelope tube bundle is

$$D_t = 1.1076s(nZ)^{0,4987} = 1 \text{ m},$$

where $s = 1.8d_o$ – step between the tubes.

The inner diameter of the heater body is

$$D_{in} = D_t + 1.5s = 1.05 \text{ m}.$$

The equation for the heat balance of the heat exchanger 2 is

$$G_1 \cdot C_p \cdot (T_3 - T_2) = G_3 \cdot C_p^a \cdot (T_7 - T_6),$$

where C_p – specific heat of water; C_p^a – specific heat of air.

From the heat balance equation $G_3 = 140.3$ kg/s.

Adopted for the heat exchanger 2 tube outer diameter $D_o = 0.019$ to 0.001 m, the inner diameter of tubing wall thickness $D_{in} = 0.017$ m, water velocity in the tubes take w = 1 m/s.

Number of tubes in the tube bundle heat exchanger is equal to

$$n = \frac{G_1}{w \cdot f \cdot \rho} = 98.$$

Coefficients of heat transfer for the heat exchanger 2 are

$$\alpha_1^{''} = Nu \frac{\lambda_l}{d_e} = 12938.2 \frac{W}{m^2 \cdot K}.$$

The tubes in the heat exchanger design with fins with a pitch of 0.006 m with a wall thickness of 0.001 m and a rib height of 0.019 m. Then the number of Nusselt adjusts for finning tubes surface [8].

$$\alpha_2^{''} = Nu \frac{\lambda_a}{d_e} = 43.38 \frac{W}{m^2 \cdot K},$$

where Nu – Nusselt number; d_e – equivalent diameter; λ_l – thermal conductivity of the water; λ_a – air thermal conductivity.

The heat transfer coefficient for the designed heater is

$$k = \frac{1}{\frac{d_{av}}{\alpha_1 \cdot d_{in}} + \frac{d_{av}}{2\pi \cdot \lambda_w} \cdot \ln\left(\frac{d_{in}}{d_o}\right) + \frac{d_{av}}{\alpha_2 d_o}} = 64.94 \frac{W}{m^2 \cdot K}.$$

The average temperature difference in the heater determined by the formula

$$\Delta t = \frac{\Delta t_b - \Delta t_s}{\ln\left(\frac{\Delta t_b}{\Delta t_i}\right)}, \text{ as } \frac{\Delta t_b}{\Delta t_s} > 1.7,$$

where $\Delta t_b, \Delta t_s$ – a bigger and a smaller temperature difference (Fig. 8).

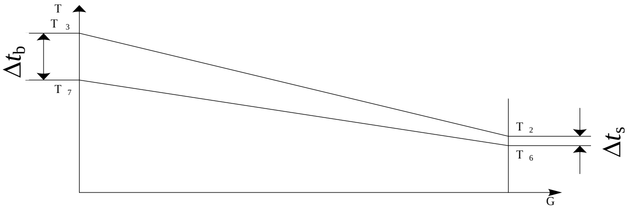

Fig. 8. The process of heating water in a current heater

The required heat transfer surface area of the heater is:

$$F = \frac{Q}{k \cdot \Delta t} = 4653 \text{ m}^2.$$

The length of the tube bundle is

$$L = \frac{F}{\pi \cdot d_{av} \cdot n} = 27442 \text{ m.}$$

With a length of tubing 5 m the number of turns is equal to

$$Z = \frac{L}{3} = 5488.$$

Then the diameter of the envelope tube bundle is

$$D_t = 1.1076s(nZ)^{0.4987} = 21 \text{ m},$$

where $s = 1.8d_o$ – step between the tubes.

The inner diameter of the heater body is

$$D_{in} = D_t + 1.5s = 21.05 \text{ m}.$$

ECONOMIC CALCULATION OF THE SYSTEM

Required cooling water heaters to ensure the provision, which should ensure the flow rate of 140 kg/s. Fan Soler & Palau HCBT/4-900/H-XV5 axis gives the flow rate of 15.5 kg/s, so 9 such units give the required air flow. For convenience of construction and operation of the heat exchangers 9 can be used with a diameter of 2 m and a single fan or each vary their number and size. The cost of one fan is currently 55596 UAH. The mass of material required for the heat exchanger was 468 kg for the heat exchanger 1 body (steel material 20), and 15444 kg for one group of heat exchangers 2 bodies (steel material 20), as well as 261.3 kg for the heat exchanger 1 tubes (12X18H10T material) and 19556.7 kg for heat exchangers 2 tubes (copper material). Estimated cost of the material required for the manufacture of heat exchangers amounted to 24375 UAH for the heat exchanger 1 and 1863091 UAH for the heat exchanger 2, we introduce the cost factor for manufacturing the heat exchanger is equal to 3, then the price will be 73125 UAH and 5589273 UAH respectively. The pump unit K90/20 is able to provide the required parameters in the system, it cost 4897 UAH, subject to a reserve pump for each circuit requires 4 of the pump. Total estimated value of the overall system of pipelines, excluding costs 6182350 UAH.

CONCLUSIONS

The scheme of the autonomous cooling system of the spent fuel pool is shown in Fig. 2, the work of the system in nodalization scheme of the spent fuel pool is implemented, the results of the calculations are shown (see Figs. 3a, 3b, 4a, 4b, 5a, 5b, 5c). The time during which the operation must be entered into the system is defined (see Table). The situation with an emergency active zone unloading in which the compartment 3 (see Fig. 5b) is completely filled is calculated. To achieve the aims nodalization scheme of the spent fuel pool has been developed, as well as to determine the minimum required parameters of the cooling system of the spent fuel pool, minimum required cooling water flow is 50 m^3/h, and the minimum required cooling water temperature was 60 °C, the most conservative variant of these options amounted to 80 m^3/h and 40 °C, respectively.

During the work calculations of heat exchangers and network parameters are defined, necessary for the implementation of the proposed water cooling system storage pool under the most conservative version of the accident.

This work reflects the situation with the real distribution of power of the residual energy in the compartments of the spent fuel pool, as well as the most conservative version of the emergency uploading of active zone is done in the cassette compartment N 3. The results of calculation determines the required parameters of the cooling system, which can be obtained using a small centrifugal pumps, the most cumbersome, despite the fin tubes, it is water cooling unit with air, which is also, as the cooling water circuit cooling pool can be installed permanently. In general, such a system can be implemented at nuclear power plants with WWER-1000.

The estimated cost of the system equipment amounted to 6182350 UAH.

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АВТОНОМНАЯ СИСТЕМА ОХЛАЖДЕНИЯ БАССЕЙНА ВЫДЕРЖКИ ОТРАБОТАННОГО ЯДЕРНОГО ТОПЛИВА НА АЭС С РЕАКТОРОМ ВВЭР-1000

О.П. Ищенко

Рассмотрена проблема охлаждения воды в бассейне выдержки при обесточивании. Построена нодализационная схема бассейна выдержки, разработанная с помощью расчетного кода MELCOR. Приведены исходные данные расчетов системы охлаждения и продемонстрирована схема автономной системы охлаждения бассейна выдержки. Приведены результаты моделирования функционирования данной системы. Проведен анализ полученных результатов моделирования. Выполнен расчет оборудования системы охлаждения воды бассейна выдержки, определены необходимые параметры сети и ориентировочная стоимость системы охлаждения.

АВТОНОМНА СИСТЕМА ОХОЛОДЖЕННЯ БАСЕЙНУ ВИТРИМКИ ВІДПРАЦЬОВАНОГО ЯДЕРНОГО ПАЛИВА НА АЕС З РЕАКТОРОМ ВВЕР-1000

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Розглянуто проблему охолодження води в басейні витримки при знеструмленні. Побудовано нодалізаційну схему басейну витримки, що розроблена за допомогою розрахункового коду MELCOR. Наведено вихідні дані розрахунків системи охолодження і продемонстровано схему автономної системи охолодження басейну витримки. Наведено результати моделювання функціонування даної системи. Проведено аналіз отриманих результатів моделювання. Виконано розрахунок обладнання системи охолодження води басейну витримки, визначені необхідні параметри мережі і орієнтовна вартість системи охолодження.