HEAT EXCHANGERS ON A BASIS LOWTEMPERATURE HEAT PIPES FOR AUTONOMOUS EMERGENCY WWER COOLDOWN SYSTEMS

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Abstract

The new circuits of WWER NPP independent passive emergency reactor cooldown systems with use lowtemperature heat pipes heat exchangers for conditions complete unit long-term deenergization is considered. The circuits of emergency reactor cooldown systems and emergency repair cooldown are resulted.

TOPICAL CHARACTER OF THE PROBLEM

A complete prolonged de-energizing of the NPP power unit is one of the reasons for the most dangerous emergency leading to the maximum emergency. The creation of new passive systems, whose the functioning is achieved independent of the actions of personnel and fitness for work of the active protective systems, is the most effective means of increasing of a nuclear power reactors safety in today's development stage of the nuclear branch. In connection with this the development, research and introduction of the fundamentally new technical solutions, directed toward the improvement of the passive systems for the outlet of the afterheat from the reactor core with the complete prolonged loss of the power supply of its own needs are expedient.

ANALYSIS OF PROJECTS OF NEW GENERATION OF THE WWER PRHR

A use of a complex of the new passive systems is provided in the designs of the reactor plants (RP) of new generation pressured water-cooled and water-moderated power reactors WWER-640 and 1000 to ensure its safety maintenance. The system of a passive residual heat removal (PRHR) of the WWER-640/V-407 project carries out reactor cooling and afterheat outlet under the conditions of the complete de-energizing of power unit. In this system steam generators (SG) and external heat exchangers of an emergency cooling, submerged in the tanks of an emergency of heat outlet. Tanks are placed out of containment and hermetically sealed shell [1, 2]. At afterheat outlet a condensation of secondary circuit vapor occurs due to cooling by water from tanks of an emergency of heat outlet. In the PRHR project of the NPP-92 with WWER-1000/V-392 [3] a condensation of secondary circuit vapor has to occur in air exchanger-condensers that prepared from finned pipes. There are control systems of the of the cooling surrounding air speed by slide device in the dependence on the pressure of secondary circuit in air exchanger-condensers

Steam generators as the intermediate heat exchangers of cooling are used in both versions of PRHR. Unfortunately, an experience of operating of horizontal steam generators of the PGV type testifies about their insufficient operational reliability [4-6]. Furthermore, continuous operation of SG when operational standards are exceeded leads to reduction in the indices of its reliability, that is fraught with a substantial increase in a radioactivity of working media and equipment for secondary circuit, ejections and discharges of radio nuclides with NPP into the environment [7]. Contribution of a leak from the first circuit to the second one as an initial event into summary failure rate of active zone (FRAZ) can be 35.5 % (small leaks) in a SG of NPP with WWER-1000/B-308 or 18.47 % (mid leaks) in a SG of NPP with WWER-1000/B-320. In a SG of NPP with WWER-440/B-312 a contribution of a mid leak can be $1.86 \cdot 10^{-5}$ per year with longitudinal contribution of 23.0 %.

Realization of PRHR for the emergency cooling when de-energizing with prolonged outlet of an afterheat through SG as basic intermediate heat exchanger can encounter with the number of essential problems. Depressurization of one or several steam generators will complicate the flow of emergency process, since due to the large difference of pressures the contaminated heat transfer agent of a first circuit will penetrate into an intermediate circuit. In this case radioactivity is extended outside of basic barriers of safety, as an intermediate circuit is taken out of a hermetically sealed shell. Furthermore, a pressure change in SG because of its tube system depressurization will lead to disruption of work of a slide device passive regulator of air exchanger-condenser.

It is desirable to use SG as a heat exchanger of the initial stage of the emergency cooling regime since a steam generator is a basic element of the steam-producing installation and has the largest heat exchange surface. Steam generator for the first hour of emergency operation will ensure the outlet of the essential portion of the afterheat due to an efficient located volume of boiler water. Further stage of the outlet of heat is prolonged, and it is desirable to ensure with the autonomous passive system, which has the high indices of the reliability, independently of unpredictable emergency conditions.

SCHEMATIC MODEL OF AUTONOMOUS PRHR ON BASIS OF HEAT PIPES

A schematic diagram of the PRHR presented in Fig. 1 is proposed to afterheat outlet and prevent an emergency in case of a power unit de-energizing by the duration more than one hour. Cooling of reactor 1 is organized at a natural circulation (NC) of a heat-transfer agent of a first circuit 2 and intermediate circuit 3, in which a heat transfer is accomplished from an autonomous intermediate heat exchanger of an emergency cooling (HEEC) 4 to external heat exchanger 5, then heat is transferred to a final absorber.

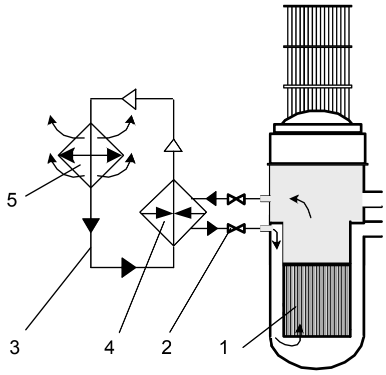

Fig. 1. Schematic diagram of an autonomous passive system of an afterheat outlet to final absorber: 1 – reactor, 2 – first circuit of emergency cooling, 3 – intermediate circuit of emergency cooling, 4 – intermediate heat exchanger of emergency cooling on HP, 5 – surface of heat withdrawal to final absorber

One of the effective methods of increasing a heat withdrawal reliability in the emergencies is use of heat exchange equipment and systems on basis of locked evaporative and condensational devices – low-temperature heat pipes (HP) and two-phase thermosyphons (TPTS) [8-10]. The major advantage of such heat exchangers is the fact that each of elements forming a heat exchange surface is an autonomous locked intermediate heat transfer loop that ensures a reliability of separation of a first circuit heat-transfer agent and cooling medium. Depressurization of one or several HP (TPTS) does not affect the fitness for work of entire heat exchanger; therefore an assembling of HP (TPTS) can be considered as the system of the parallel-connected independent elements. At that time depressurization of one tube of SG heat exchange surface leads to its refusal and, as it was noted above, at implementation PRHR with circuit taken out of a hermetically sealed shell to propagation of radioactivity for basic barriers of safety.

Heat exchange installations on HP and TPTS basis possess by low thermal resistance, high compactness because of absence of cameras for supply (outlet) of heat transfer agent and, in a number of cases, it ensures more effective heat transfer in comparison with traditional heat exchangers. Corresponding organization of being transferred heat media motion in an intertube space of such heat exchangers both in the zone of heat supply and heat withdrawal, allows to obtain minimum hydraulic resistance on circuits of external heat transfer agent and gives a possibility to use its natural circulation (NC). In connection with this it is expedient to use heat exchanges apparatus (HEA) on basis HP and TPTS in the systems of emergency of nucleate power facilities (NPF), requirements of increased reliability, safety and effectiveness to which occupy the determining place [11].

For conditions of the considered emergency a calculated modelling with use of the thermohydraulic code RELAP5/MOD3.2 of the afterheat outlet regime of the reactor WWER-1000 was carried out [12]. The determination of possible time of cooling through SG was the goal of this simulation, located reserve of boiler water was taken into account. The results of calculated experiment show that an increase of saturation pressure and, respectively, temperature begin in SG, off from the users, under the conditions for its continuous generation. NC of heat transfer agent through a contour "reactor – SG – reactor" ensures an outlet of heat from A3 to second contour. However, the level of boiler water is reduced because of the periodic undermining of SG safety valves, and after 1 hour 23 minutes SG is dried completely (Fig. 2).

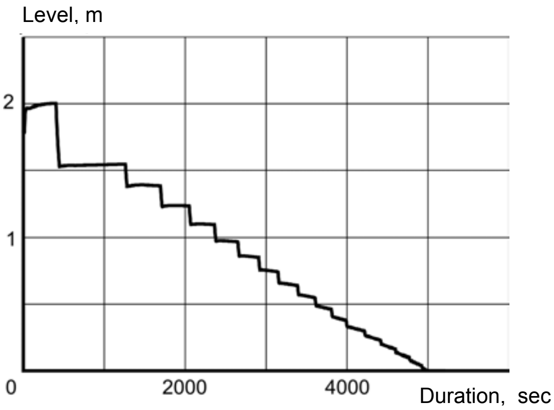

Fig. 2. Change of a weight level of SG boiler water under conditions of a reactor plant emergency cooling at complete de-energizing

It should be noted that the obtained results practically coincide with data of the "Hydropress" Experimental Design Office [13] obtained with aid of RELAP5/MOD3.2, ATHLET1.2A and DYNAMICS-97 codes for the RU B-392 project. According to that data, the time of a total loss of boiler water in SG is 1 hour of 46 min., 1 hour of 43 min. and 2 hours of 5 min. respectively. Consequently, assuming a conservative estimation of the time of effective heat withdrawal from an active zone through SG during approximately 1 hour of 20 min. from the moment of a loss of its own needs of power supply, it is possible to determine the overheat power for this period, which will be 38-40 MW (Fig. 3) [14]. In the considered situation it is proposed to realize a further outlet of afterheat with help of an autonomous PRHR since its working capacity doesn't depend on the state of secondary circuit.

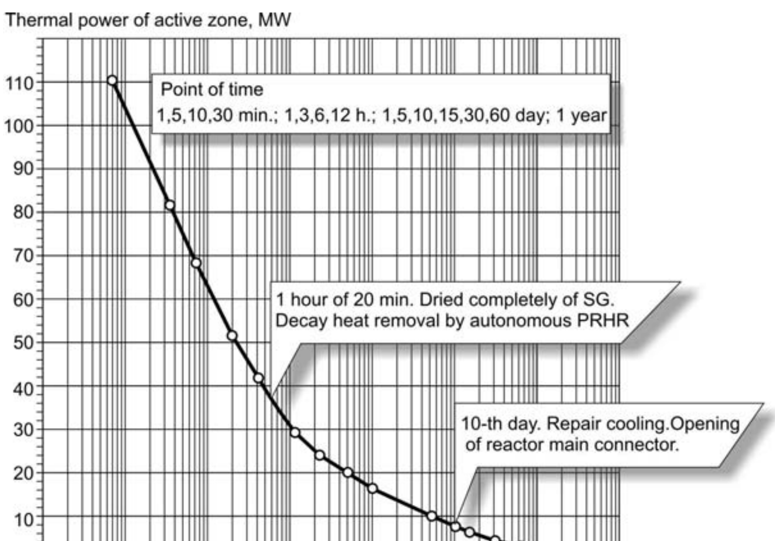

Fig. 3. Power of an afterheat of active zone after stop of reactor (without taking into account the delayed neutrons)

AUTONOMOUS PRHR ON THE BASIS OF TWO-PHASE THERMOSYPHONS

The presented in Fig. 4autonomous PRHR for a project of NPP with WWER ensures an outlet of the afterheat when the accident with complete prolonged de-energizing occurs. In the proposed scheme an outlet of afterheat is accomplished at a natural circulation through an intermediate heat exchanger of emergency cooling (HEEC) and intermediate two-phase circuit during a long time. An intermediate two-phase circuit heat transfer through an exchanger-condenser to atmospheric air. An intermediate HEEC is designed on a basis of low temperature two-phase thermosyphons.

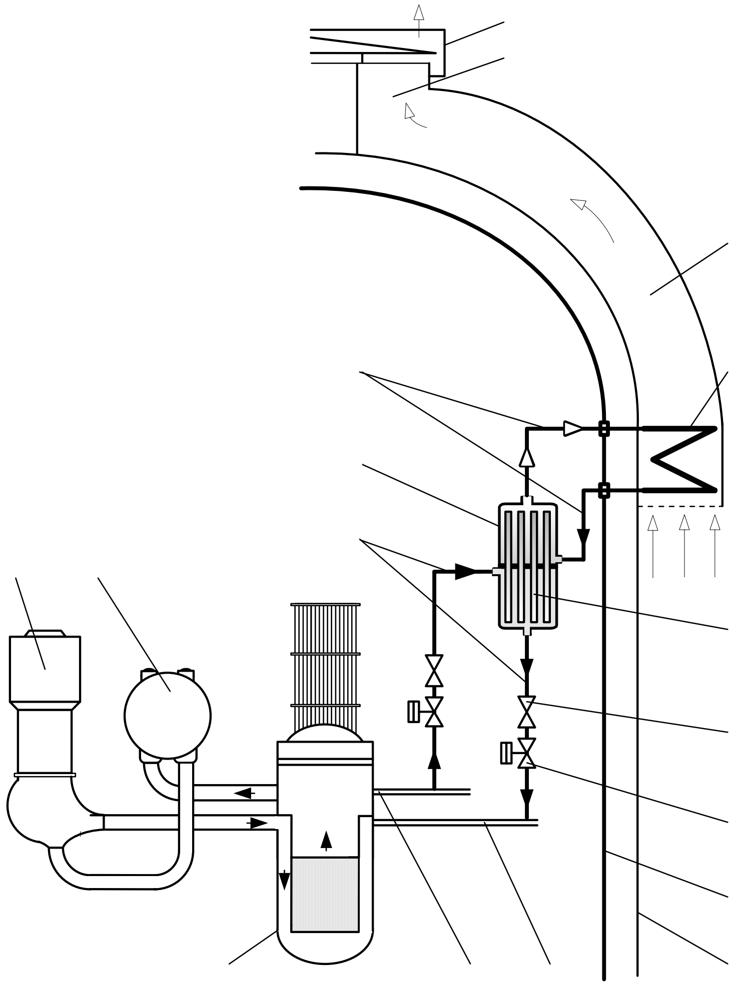

Fig. 4. Autonomous PRHR with intermediate TOAR on basis TPTS for NPP with WWER: 1 – reactor, 2 – circuit of cooling, 3 – HECC on basis of thermosyphons, 4 – intermediate cooling circuit, 5 – assemblage of TPTS, 6 – coupler tunnel of PRHR, 7 – air exchanger-condenser, 8 – valve, 9 – diaphragm valve, 10, 11 – branch pipes of ECCS, 12 – hermetically sealed shell, 13 –containment, 14 – SG, 15 – Main Coolant Pump (MCP), 16 – outlet collector header of PRHR, 17 – deflector

PRHR represents four autonomous cooling circuits consisting of a working fluid circuit 2, intermediate HEEC 3 on basis of two TPTS, air exchanger-condenser out of containment 13, hermetically sealed shell 12. Assemblage of TPTS serves as an additional locked intermediate circuit between first outline 2 and intermediate circuit 4, which is led out of hermetically sealed-zone. So construction substantially elevates an ecological safety in the considered emergency. Heat transfer in an intermediate circuit is accomplished at boiling on external surface of TPTS 5 condensers of intermediate HEEC 3 and condensations in exchanger-condenser 7 [15]. Outlet of heat from exchanger-condenser 7 to atmospheric air is analogous with a scheme of a PRHR of the NPP-92 project.

Heat transferring elements of HEEC 3 are assemblage of low temperature cylindrical thermosyphons 5 placed vertically in a triangular framework. There is a tube desk located in a center section of heat exchanger (Fig. 5), this pipe desk is a bearing component TPTS assemblage. HEEC has a cylindrical body, there are branch pipes for supply of hot working fluid of a first circuit and condensate from intermediate circuit are placed on its generatrixes, branch pipes for outlet cooled working fluid of a first circuit and steam of an intermediate circuit are located on front caps. The working fluid of TPTS and intermediate circuit of cooling is water.

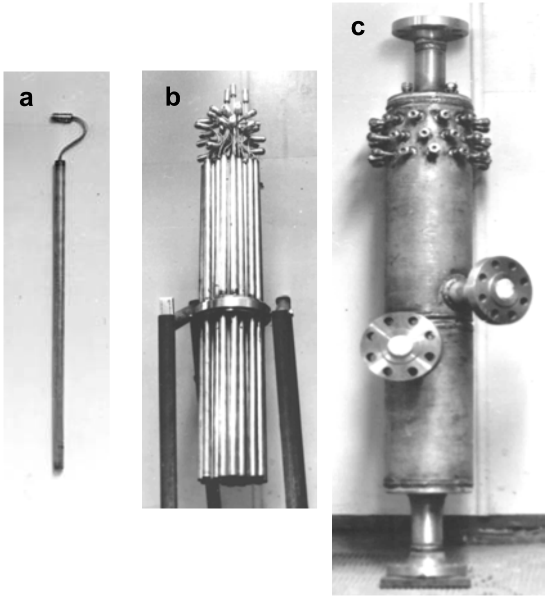

Fig. 5. Experimental heat exchanger of emergency cooling on basis of TPTS: a) ordinary thermosyphon with filling stem, b) assemblage of TPTS with central tube desk, c) thermosyphon heat exchanger as an assembly

Thermosyphons of HEEC and an intermediate circuit are vacuumized before filling with working fluid. System is filled up with intermediate working fluid, it is in the regime of constant operating availability during all operating period of a reactor unit. In the holding pattern all working fluid of an intermediate circuit is existed in HEEC. In this case working fluid is absent in a cavity of exchanger-condenser, therefore there is not danger of its freezing at minus temperatures of ambient air in a winter season. Stop valve, which ensures an enable of reactor unit to PRHR, is erected only on conduits of a first contour of a cooling circuit 2 (Fig. 4). Valve 8 with a hand drive ensures an intercepting of a PRHR channel from a first circuit for conducting of maintenance and repairing of equipment and systems. Before a preventative maintenance of unit the valve 8 is shut and during a repair it is always the closed position. During operation of a reactor unit the valve 8 is always opened.

Valve 9 is intended for the automatic enable of a PRHR channel to reactor unit in an emergency when a de-energizing occurs, it has a diaphragm drive with pull-back spring. In the period of reactor unit operation the valve 9 is closed in the holding pattern. Control response for its opening is formed with the necessary time delay for the non-admission of uncontrolled cooling at short-term loss of power supply for its own needs. Principle of its opening passiveness is ensured by de-energizing of the auxiliary magnetic valve solenoid, which opens the line of slow deaeration from the cavity above a membrane. Valve opens by a spring.

When de-energizing occurs, the reactor protection operates and the major heat remover is realized through SG up to 1.4% of the nominal power. Beginning from this level of an afterheat, cooling of a reactor unit is ensured by the considered autonomous passive system with HEEC based on two-phase thermosyphons.

PASSIVE SYSTEM OF EMERGENCY REPAIR COOLING ON BASIS OF ANNULAR TWO-PHASE THERMOSIPHONS

The situation connected with the curtailment of an afterheat outlet in preventative maintenance period at demounted upper block (UB) of reactor, including the regime of repair cooling and refuelling is non-project emergency state. At failure of the system of emergency and plan cooling a warming-up of the reactor active zone occures. A time from the moment of stopping of an afterheat outlet to the moment of bareing of the active zone and warming-up of a heat-evoluting elements up to the temperature of 150 °C is 5-6 or 2 hours depending on the initial level of heat-transfer agent in reactor [16]. If a stopping of an afterheat outlet is caused by a complete prolonged de-energizing, it will not be possible to revivify a forced circulation in the backup cooling systems. Under these conditions the autonomous PRHR as well is proposed to provide a safety of reactor unit in a composition of emergency systems. In this case the guarantee of reliable heat removal is a presence of conditions for a heat-transfer agent natural circulation of the first circuit through a heat-exchange equipment.

On the power units NNP with WWER a heat exchanger on the basis of annular TPTS, placed in the volume of the tunnels of revision or of a spent fuel pit can be used as a heat exchange device for the emergency heat withdrawal. There is a lay-out diagram of the PRHR for averting of the emergency at de-energizing during the preventative maintenance is shown in Fig. 6. In this PRHR an outlet of afterheat to water, which floods volumes of tunnels of revision and pond of wet overload, is foreseen [17]. Natural circulation of a heat-transfer agent of the first circuit is realized along the cooling loop that is connected up to a reactor 1 through branch pipes of emergency core cooling system (ECCS) (inner diameter 300 mm) with help of a group of accessories 8 with electromagnetic and pneumatic drives.

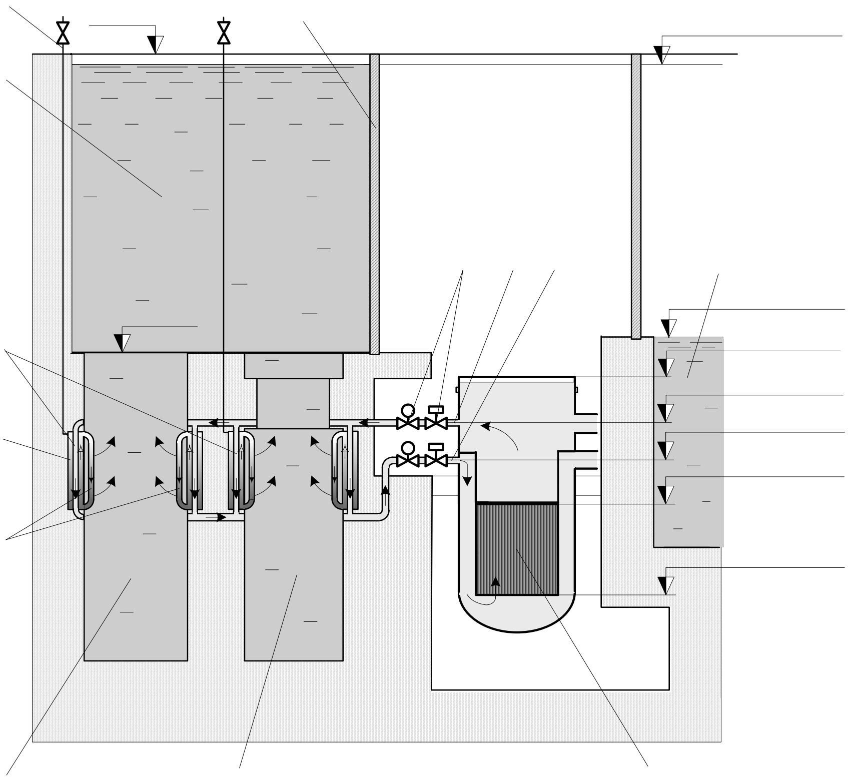

Fig. 6. Passive system of emergency cooling with an afterheat outlet to a volume of the tunnels of revision and pond of wet overload with help of intermediate annular TPTS: 1 – reactor, 2 – "hot" pipe-line of the emergency cooling loop, 3 – intermediate annular TPTS, 4 – evaporators of TPTS, 5 – condensers of TPTS, 6 – tunnel of revision of the safety tubes block, 7 – tunnel of revision of vessel internal, 8 stop valve, 9 – "cold" pipe-line of the emergency cooling loop, 10 – pond of wet overload, 11 – line of vacuumization and filling of TPTS, 12 – stop beam, 13 – spent fuel pit

Final absorber with a volume of about 800 cubic meters is formed with water that fills the tunnels of revision of the relief tubes block 6, the vessel internals 7 and the pond of wet overload 10. The mentioned tunnels are used only during a repair of block, in which the vessel internals are placed at its unloading from reactor and at conducting of its revision. Tunnels of revision are empty and not enabled during all operating period. After transfer operation the tunnels are drained.

An outlet of after-heat is realized with help of a natural circulation of a heat-transfer agent of the first circuitthrough the “hot” transmission pipe-line 2. The intermediate heat exchangers of cooling are placed concentrically around the tunnels of revision 6 and 7. The intermediate heat exchangers represents the two-phase thermosyphons 3. An evaporator of the annular thermosyphon is the vertical tube surface 4, inside of which a heat-transfer agent of the first circuit circulates. An intermediate working fluid of TPTS evaporates on the outer surfaces of tubes 4, rises to the upper cavity of TPTS and then into condensers 5 that placed into a volume of the tunnels of revision. Heat transfer is realized from a heat-transfer agent of the first circuit to an intermediate working fluid of TPTS and then to a water in tunnels 6, 7 and compartment 10. Recovery of a heat-transfer agent of the first circuit is practiced along the “cold” transmission pipe-line 9.

As afterheat will be absorbed, a temperature of the water in the tunnels and pond of wet overload will increase, then a water will begin to evaporate. The total volume of final absorbent is approximately 1350 cubic meters, and the effective heat outlet from a few hours to several days at an emergency cooling can be ensured. It depends on the level of afterheat, its peak value is 7-8 MW (Fig. 3). Moreover, this PRHR will be able to work both at the emergency repair cooling with opened main connector of reactor and demounted upper block and to remove part of heat under the conditions of the emergency cooling of the “hot” reactor unit. Taking into account the available supply of water (final absorber), a personal has an additional time for restoring a power supply for own needs, compensation of a loss of the evaporated water and guarantee of the issued cooling systems capacity for work.

PASSIVE SYSTEM OF EMERGENCY REPAIR COOLING ON THE BASIS OF HEAT PIPES

An outlet of the afterheat at an emergency repair cooling can be organized also into a volume of the spent fuel pit of a used nuclear fuel. The heat exchanger placed in a spent fuel pit and ensuring heat removal of the first circuit at switching-off of an active safety systems is used in the system of passive emergency cooling of the “hot” reactor unit by the project AP-600/1000 [18]. The cooling system arrangement with using of spent fuel pit is very reliable in the considered situation. However, this system has essential defaults. Foremost, the first circuit will be penetrate into a spent fuel pit at depressurization of collecting heat exchanger of the emergency cooling. Deteriorated radiation environment in the sealed zone will complicate situation essentially even the losses of heat-transfer agent will be compensated. Secondly, the system of a similar arrangement becomes non-serviceable in the regime of emergency repair cooling. Opening of the main connector of reactor imposes certain constraints on the organization of a natural circulation of the first circuit. This circulation is possible only at the heat exchanger location not higher than the main connector of reactor is placed, or else it will be open circuit of a natural circulation. Therefore the arrangement of a spent fuel pit of the energetic block AP-600/1000 above a reactor doesn’t allow to use this volume of water for a repair cooling with opened main connector of reactor.

The arrangement of a spent fuel pit of NNP with WWER-1000 on the level of the upper half of a reactor tunnel is more perspective for the organization of repair cooling. In this case an available in a pond volume of water ensures an effective heat remove at an emergency cooling: at 221.9 cubic meters in both compartments of a spent fuel piton the low regulation bound and at 423 cubic meters on the upper emergency bound respectively [19].

The diagram of the proposed passive system of emergency repair cooling through an intermediate unpackaged heat exchanger with heat pipes is presented in Fig. 7. Heat exchanger is placed in a cooling pond. A connection of the emergency cooling heat exchanger 1 with the first circuit is realized through the upper and lower branch pipes with inner diameters 300 mm, as in the above mentioned schemes.

The heat exchanger of a repair coolinf has a number of design features. The evaporative part of the HP assemblage 4 is located out of the pond volume. It gives a possibility don’t output a heat-transfer agent of the first circuit in a space of the spent fuel pit directly and so to limit a possible extension of a radioactive contamination in the pond at a depressurization from a side of the first circuit. An application of arterial heat pipes will guarantee a working capacity of the heat exchanger with horizontal evaporative sections. The condensation zone 3 of a HP assemblage is vertical, it is outputs in a space of the spent fuel pit [20].

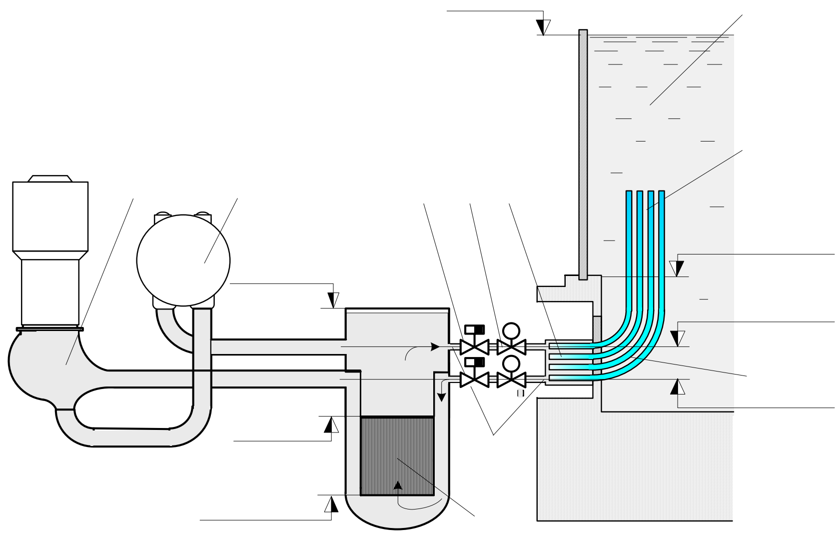

Fig. 7. Passive system of emergency repair cooling of WWER with outlet of afterheat to the spent fuel pitof used nuclear fuel through the heat exchanger on basis of HP: 1 – cooling heat exchanger with HP, 2 – cooling pond, 3 – condensers of HP, 4 –evaporators of HP, 5 – pipe-lines of ECCS, 6 – stop valve with pneumatic drive, 7 – stop valve with electromagnetic drive, 8 – reactor, 9 – SG, 10 – MCP

CONCLUSION

A development of design concepts of PRHR of reactor units is the natural process of perfection of the systems equipment, which determine reliability and safety of the NPP energetic blocks at emergency situations. Using a heat exchange apparatus on basis of HP and TPTS it is possible to create on principle new PRHR of NPP with WWER, which will be ensure an emergency reactor cooling at nonproject emergency under the conditions of complete prolonged de-energizing.

Application of the considered systems to the safety systems of the reactor units with WWER operated today will require certain changes of the energetic block project. Therefore the realization of this task most probably is possible at development of the new generation of NPP reactor units with WWER. Also it can be practiced in the stage of commissioning of energetic blocks of the NPP, whose building was “frozen” after the Chernobyl emergency in 1986. The considered autonomous systems of emergency cooling with HP and TPTS are proposed for improving of PRHR of the NPP energetic blocks of the third generation with WWER-640, 1000, 1500 and for a modernization of safety systems of the NPP energetic blocks with WWER-440 and WWER-1000 operated at present. The aim is to increase the reliability and safety indexes of basic NPP equipment, to create the engineering and organizational prerequisites for a prolongation of a work resource of acting NPP.

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