NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 6(2): 105–111
DOI 10.3897/nucet.6.55220

Research Article

Conceptual issues of the cold filter trap development for the sodium coolant purification in fast-neutron reactors*

Viktor V. Alekseev[1], Yuliya A. Kuzina[1], Aleksandr P. Sorokin[1]

1 *JSC "SSC RF-IPPE n.a. A.I. Leypunsky"1 Bondarenko Sq., Obninsk, Kaluga Reg., 249033, Russia*

Corresponding author: Viktor V. Alekseev (alexeev@ippe.ru)

Academic editor: Boris Balakin ♦ **Received** 11 October 2019 ♦ **Accepted** 13 April 2020 ♦ **Published** 25 June 2020

Citation: Alekseev VV, Kuzina YuA, Sorokin AP (2020) Conceptual issues of the cold filter trap development for the sodium coolant purification in fast-neutron reactors. Nuclear Energy and Technology 6(2): 105–111. https://doi.org/10.3897/nucet.6.55220

Abstract

The paper presents the results of studying the peculiarities of heat and mass exchange in cold traps for the sodium purification of impurities in fast reactor circuits both in dedicated test areas simulating various trap components (isothermal sump, nonisothermal sump, filters, final cooling area) and in trap prototype models. As a result, a scientific rationale has been formed for developing traps of a unique design for various reactors. The impurity capacity of the traps is three to four times as high as that of the best foreign counterparts. Tests have shown these to be highly efficient in purifying sodium of oxygen and hydrogen and much less efficient in sodium purification of corrosion products and carbon. Taking into account the leakage of radioactive sodium during operation of the BN-600 reactor primary circuit traps, a decision was made to install the purification system in the reactor tank to improve the safety of the large fast reactor. It was resolved to exclude the accumulation of hydrogen in the primary circuit traps in nominal conditions. Two trap designs, with argon and sodium cooling, are discussed. It has been shown that operation of the reactor purification system with argon cooling will require 20 trap replacements during the reactor operating life and seven replacements if the deposition of hydrogen into the primary circuit cold traps is excluded. The sodium-cooled version of the trap built in the reactor tank has the same overall dimensions as the argon-cooled trap. The cooling sodium circulates in two trains: outside the jacketed working space body (up to 30% of the flow rate) and in the coil inside of the working space (up to 70% of the flow rate). Updates have been proposed to the trap design based on the calculations using the codes simulating the in-trap processes of heat and mass exchange.

Keywords

Fast reactors, sodium coolant, cold trap, reactor tank, experiment, codes, thermal hydraulics, mass exchange, impurities, oxygen, hydrogen, argon cooling, sodium cooling

Introduction

Cold traps are the main devices for the purification of sodium in the fast reactor circuits. Studies in this field have been under way since the time the first fast-neutron sodium-cooled reactors were built. The peculiarities of the hydrodynamic processes involved in the heat and mass exchange in such traps were investigated. Studies were

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2020, n. 1, pp. 121–133.

conducted both in dedicated test areas simulating different cold trap components and using prototype models of ex-vessel traps designed at IPPE and OKBM. An empirical approach was used primarily which has made it possible to achieve good results.

A domestic cold trap of a unique design has been developed and justified the performance of which surpasses that of the best foreign counterparts (Kozlov et al. 1983, 2007). This trap design consists of three serially connected areas: the nonisothermal sump area, the final cooling area, and the isothermal filter area (Fig. 1).

To improve the reactor safety, given that radioactive sodium leakage had been taking place during operation of the BN-600 reactor primary circuit cold traps, a decision was made in the process of developing the large fast-neutron sodium-cooled reactor to install the purification system in the reactor tank (Rachkov et al. 2010, Vasilyev et al. 2016). The purification system's key components are the cold traps built in the reactor tank.

Comparing various cold purification systems shows that trap compartments and heated sodium pipelines are required for ex-vessel cold traps, while in-tank cold traps require spent trap storage pits and a trap recharging system. A combined purification system version has been proposed which comprises one fixed large-size ex-vessel trap and two replaceable in-vessel traps of a limited capacity.

The development of the in-tank trap is based on earlier findings in the field of sodium coolant technology. The goal is to improve the trap in terms of safety, cost effectiveness and environmental friendliness. The first versions of such traps have been developed (Kozlov et al. 2012, Alekseev et al. 2013, Kalyakin et al. 2014, Sorokin and Trufanov 2017). For the initial consideration, argon has been selected as the coolant for the trap cooling. Sodium and a eutectic sodium-potassium alloy are also proposed as alternative coolants. This involves the use of recently developed methods and codes for simulating numerically complex processes of spatial mass transport and impurity precipitation inside of the traps (Varseyev et al. 2014, Alekseev et al. 2015a, 2015b, 2017).

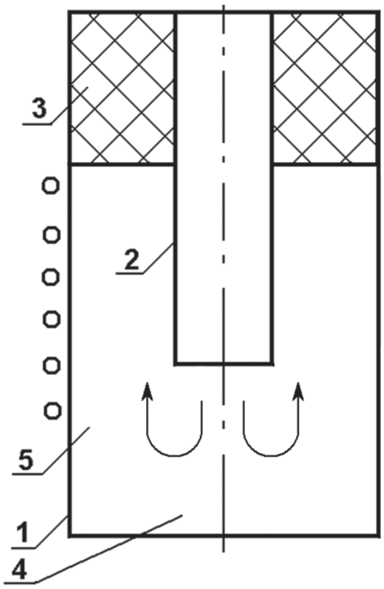

Figure 1. Cold trap schematic design: 1 – trap body; 2 – supply channel; 3 – filter; 4 – sump; 5 – cooling area.

Experience in domestic cold trap development

Structural concepts of the cold traps for the BR-10, BN-350, and BN-600 reactors are shown in Figs 2, 3 (Kozlov et al. 1983, 2007). It should be noted that various coolants are used for the cold trap cooling.

The cold trap studies aimed to acquire information on the processes of hydrodynamics, heat and mass exchange, and impurity distribution within the traps, as well as to investigate the trap performance. Mode parameters were monitored to this end. Updates on the impurity distribution in the trap were obtained using an ad-hoc technique of trap radiography by gamma radiation of cesium-137 with a fixed mode of the trap operation in the circuit and, after the testing was over, by analyzing the trap parts, into which the trap was cut, and the local samples taken from the trap after the cutting. Apart from a large number of test areas, six traps of different types were tested: three traps with the downward and three traps with the upward sodium movement in the cooling area. The traps were cooled with a sodium-potassium alloy (BN-350 trap prototypes) and with air (BN-600 trap prototypes). Sodium was contaminated with oxygen, hydrogen or water fed into the circuit.

Recommendations on the cold trap design were issued based on the experiments conducted at IPPE (Kozlov et al. 1983) in 1963: primary cooling was relocated to the nonisothermal sump area (area 1) with the final cooling area (area 2) and the isothermal filter area (area 3) arranged above it in series. A procedure was developed to calculate the traps of the given type, and the key design issues were considered. The constants required for the CT calculation and design were identified based on the test results.

It was shown that the confinement factor for sodium oxide and hydride (products of sodium interaction with water) was close to unity with the time for which sodium stayed in the trap being 15 to 20 min. The minimum concentration of oxygen and hydrogen in sodium after its purification in traps of different types was equal to their solubility at the trap outlet temperature. With a temperature of 120 to 150 °C, we have, respectively, the concentrations of 3 to 5 ppm and 0.02 to 0.05 ppm.

The whole range of factors was taken into account to determine the cold trap volume, V_t, and the volume of the trap areas, including the coolant weight in the facility, the intensity of the impurity sources, the time of the coolant purification in the facility, the trap life, and the required (rated) concentration of impurities in the coolant. Given that the time for which the coolant stays in the trap, τ_t, the flow rate being Q_t, shall be not less than 10 to 15 min, V_t

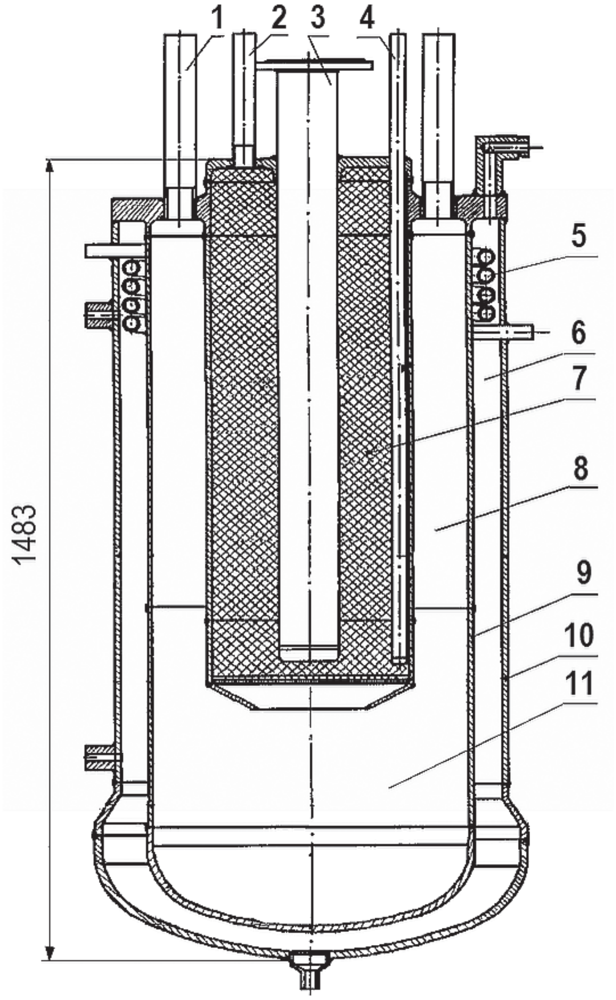

Figure 2. Design of the sodium impurity cold trap for the BR-10 reactor: 1 – sodium inlet nozzle; 2 – sodium outlet nozzle; 3 – heater cavity; 4 – thermocouple pocket; 5 – water cooling coil; 6 – toluene cavity; 7 – filter; 8 – sodium cooling channel; 9 – cold trap inner body; 10 – cold trap outer body; 11 – sump.

$= \tau_t Q_t$, three-area traps shall provide for the impurity confinement factor, β, of not less than 0.6 with the trap being clean. It will tend to unity as impurities are accumulated.

The coolant flow rate, Q_t, through the cold trap was determined from the condition of the maximum permissible impurity concentration, C_{max}, with the known intensity of the impurity sources, G_{imp}, in the facility:

$$Q_t = G_{imp}/[(C_{max} - C^{\tau}_t)\beta],$$

where C^{τ}_t is the concentration of impurities at the trap outlet at the temperature t. Knowing Q_t and τ_t, one can find V_t.

Another approach to the trap volume determination is based on the quantity of impurities accumulated by the cold trap either throughout the facility operating time or for a particular preset period of time. The test results have shown that the trap capacity, with only sodium oxide accumulated in the traps, amounts to 25 to 27% of the trap volume, one fourth of the initial trap volume being filled with impurities. With sodium oxide and sodium-water in-

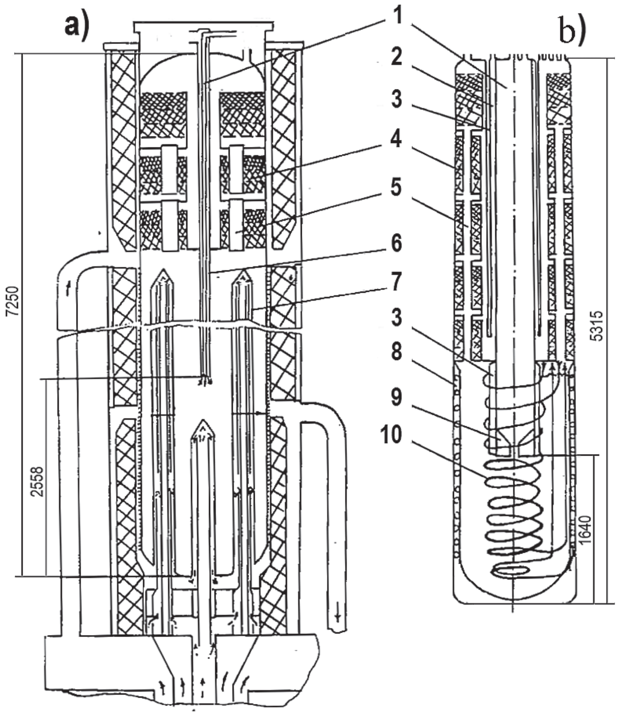

Figure 3. Designs of the sodium impurity cold traps for the BN-600 (a) and BN-350 (b) reactors: 1 – central tube; 2 – outside regenerator channel; 3 – air gap; 4 – filter; 5 – flow-through tubes; 7 – air cooling tubes; 8 – cooling jacket; 9 – cone; 10 – coil.

teraction products ((Na_2O, NaH, NaOH) accumulated in the traps, the trap capacity becomes approximately twice as low. Taking into account strict simulation methods, it was assumed in designing the cold traps for BOR-60 and BN-350 that their capacity would be equal to 10% of the volume provided that the recommendations were followed. The removal of particles with the coolant into the circulation circuit is observed as the flow rate grows sharply (by two to four times).

Toluene, dowtherm, tetraline, a sodium-potassium alloy, water, air, nitrogen, etc. were used for the cold trap cooling. Using water for cooling complicates the trap design and causes operating difficulties. For the purpose of safe operation, the heat-transfer wall needs to have two layers with a lead interlayer.

It should be noted that the use of gas cooling takes into account specific requirements to the air discharge point with regard for the potentiality of an emergency metal leakage in the trap, and extra spaces shall be provided to deploy the cooling system (air ducts, fans, etc.). It is required to provide the alarm for the coolant escape into the gas system and simultaneous disconnection of the cold trap and the gas system with the use of valves.

Cold traps for secondary circuits, as those for primary circuits, operate without replacement but each of them is regenerated due to a growth in the hydraulic resistance or because of difficulties with supporting their operation. Based on a thermodynamic analysis, methods for the cold trap regeneration have been proposed and justified, allowing their performance to be restored by converting the impurities accumulated in the trap to a caustic phase, the temperature of which does not exceed 400 °C, and by removing it hydraulically from the cold trap. The available experience shows that the trap can be regenerated not less than thrice (Kozlov and Volchkov 1975).

In-vessel system for sodium purification of impurities

System features

The in-vessel system for sodium purification of impurities shall meet the requirements of:

- providing for the required purity of the coolant in conditions of the NPP long-term operation with rated parameters;
- having the required capacity for the impurities entering the primary coolant with regard for all of its operating modes (including emergency contamination); it is permitted to replace the purification system components during the facility operating life, the number of the replacements being defined by the NPP terms of reference but desired to be as small as possible;
- having the efficiency that guarantees the coolant purification of impurities during scheduled maintenance, refueling, and emergency contamination for the time specified in the terms of reference.

The sodium purification system built in the reactor tank has the following drawbacks:

- low efficiency due to a substantially limited sodium flow rate through the cold trap (this increases the time for the sodium purification to the required purity level);
- the need for multiple trap replacements due to the insufficient capacity of the built-in purification system because of the limited trap dimensions and number;
- complexity of the cooling system and the requirement for the trap to be continuously kept in the cooling mode (the trap out of operation shall have a temperature of 120 to 150 °C since being for a long time at the sodium environment temperature of $t_{Na} \geq 410$ °C will lead to the shut trap being prone to increased corrosion of its internals);
- the potential for the impurity-contaminated sodium to leave the overheated cold trap and enter the reactor vessel, and for hydrogen gas to form and enter the reactor tank.

The most important thing is to explore safety issues. First of all, as shown by estimates, an issue is addressed concerning the accumulation of hydrogen in the primary circuit cold traps during rated operation. Hydrogen will migrate into the secondary circuit cold traps thanks to the primary trap outlet temperature increasing to 150 °C as the previous temperature mode of the secondary circuit cold trap is maintained (the temperature at the secondary circuit trap outlet is 120 °C) and the total flow rate through the secondary circuit cold traps is over 44 m^3/h.

In-tank cold traps

Two trap designs, with argon and sodium cooling, have been proposed for the large reactor (Alekseev et al. 2013, Kalyakin et al. 2014, Sorokin and Trufanov 2017).

Argon-cooled cold trap. The initial version of such a trap built in the reactor tank was over 15 m in size, and its geometrical parameters were far from being optimal. The trap height was reduced and its geometrical parameters were somewhat optimized for the second version developed with cooling by argon pressurized to 1.5 MPa. The working space volume is 1.75 m^3 (Alekseev et al. 2013), and the estimated impurity capacity is 350 kg.

Altogether, three built-in cold traps are planned to be installed in the reactor tank. As estimates show, multiple trap replacements will be required during 60 years of the NPP operation. Some 8000 kg of impurities enter the traps throughout the operating life of an advanced large fast reactor. The cold trap working space volume is 1.75 m^3. The estimated impurity capacity of the trap is assumed to be 20%, this making 350 kg. The number of the traps in this case is 8000/350 = 23. With three traps installed in the reactor tank, 20 more traps (replacements) will be needed for the reactor lifetime.

The number of the primary circuit traps can be reduced thanks to the operation of the sodium purification system in a mode that reduces the hydrogen accumulation in the circuit. Minimizing the number of the trap replacements in the primary circuit will require a sodium flow rate of 11.5 kg/s through all of the secondary circuit cold traps. To estimate the number of the trap replacements in the primary circuit saved during 60 years, the quantity of sodium hydride the traps could retain has been determined. With the hydrogen source in the primary circuit being $6.23 \cdot 10^{-8}$ kg/s, the quantity of sodium hydride for the 60 years will be 2830 kg. Owing to the hydrogen entering from the secondary circuit through the intermediate heat exchanger walls, some 1750 kg of sodium hydride more are expected to be accumulated. Altogether, therefore, some 4580 kg of sodium hydride can be accumulated even without regard for the initial contaminations and contaminations from external sources during refueling.

The number of the saved cold trap replacements in the event of this hydrogen quantity accumulated is 13. Since 20 replacements will be needed during the reactor service life with the purification system operating based on the regular flowchart, avoiding the entry of hydrogen into the primary circuit cold traps from the secondary circuit will require as few as seven replacements.

Simultaneous operation of three traps will require not less than 16009 h (68 days) for the sodium purification after scheduled maintenance, refueling or emergency contaminations. And the time of the sodium purification of oxygen to a concentration of 10 ppm (when the reactor rated parameters can be achieved while the sodium purification is continued) is about 500 h.

To reduce the number of in-service replacements for the primary circuit cold traps built in the reactor tank and to reduce the time for the sodium purification after scheduled maintenance, refueling or emergency contamination, it is required to increase both the effective volume of the trap and its impurity capacity. To address this, calculations were performed to optimize the trap parameters and operating modes.

Sodium-cooled cold trap. Additionally, a version of a sodium-cooled cold trap built in the reactor tank has been developed. It has the same overall dimensions as the argon-cooled trap but its working space volume can be much larger. A coil has been added to the trap inside. The cooling sodium circulates in two cooling trains: outside of the jacketed working space body (up to 30% of the flow rate) and through the coil installed inside of the working space (up to 70% of the flow rate, in the trap initial operation period). Using sodium for the working space cooling instead of pressurized argon makes it possible to exclude the component having an increased potential energy and to increase the working space diameter which improves the trap performance.

The advantages of this trap version confirmed by calculations are as follows:

- sodium circuits are used to cool various devices with a high reliability and for a long time (tens of years) and can be therefore employed to cool cold traps built in the reactor tank;
- the cooling sodium entry into the primary circuit does not cause any negative effects;
- feasibility of sodium cooling, in the event of a standard trap, for traps built in the reactor tank;
- possibility for the trap's inner volume to be used with a higher cost-effectiveness if sodium is used for cooling;
- possibility for employing the NPP personnel with an experience in sodium coolant handling.

The cooling sodium circuit shall meet all of the requirements to facilities with alkaline metals. Process equipment shall be installed in individual compartments or behind a safety enclosure. Such circuit is evidently a complex and cumbersome structure. It is necessary to optimize the cooling system to simplify and make it cheaper. This can be achieved by eliminating the drain tank, the breathing tank, the purification system, and some other circuit components. Due to a relatively low temperature of the circuit, the entry of impurities into sodium will be minor, which allows the monitoring system and the sodium impurity purification system to be simplified. Simultaneously, the level of requirements to rooms, sodium equipment accommodation, and some of the auxiliary systems needs to be updated. As the result, this will require a low-inertia sodium cooling agent circulation system to be leak-tight and serviceable throughout the preset operating life.

Table 1. Comparison of the primary circuit purification systems for the BN-350 and BN-600 reactors, and for the large advanced fast-neutron reactor.

NPP PS cooling	V_{Na}, m^3	V_{CT}, m^3	CT flow rate, G_{Na},m^3/h	t^{out}_{CT}, °C	Capacity*, kg	V_{Na}/ G_{Na}, h
BN-350 PS	500	3×3	7×3	120	600×3	24
BN-600 PS	1000	8×2	8×2	120	1600×2	62
Advanced BN PS (Ar cooling)	1900	1.75×3	2.8×3	150	350×3	230
Advanced BN PS (Na cooling)	1900	1.86×3	4×3	150	441×3	160

* – Sodium oxide capacity

Comparison of fast-neutron reactor primary circuit purification systems. Studies have shown that the cold trap (CT) cooling with liquid-metal coolant will make it possible to exclude the hazard from the use of argon pressurized to 1.5 MPa and will contribute to improving the trap performance. The comparison of the primary circuit purification systems (PS) for the BN-350, BN-600, and advanced BN reactors (using sodium and argon cooling) is presented in Table 1.

The table shows that the efficiency and capacity of the purification system for the advanced argon-cooled BN reactor are nearly thrice as low as for the BN-600 reactor and nearly 2.5 times as low with sodium cooling respectively. This means that the time for the advanced reactor primary coolant purification using three argon-cooled CTs, other conditions being equal, will be nearly three times as great as for BN-600 (Alekseev et al. 2013). It should be noted that an economic analysis is required for the final selection of the cold trap version.

Optimization studies of cold traps using cold trap mass transport computational simulation procedures

The optimization studies of the cold trap design aimed to achieve the trap maximum economic and process performance. A computational model has been proposed for the thermal hydraulics and mass transport of impurities in the cold trap which is based on approximating the incompressible multi-component environment and makes it possible to simulate global spatial distributions of the coolant velocity fields, the temperatures of the coolant and structural components, and the transported impurity concentration distribution. The TURBOFLOW (Kozlov et al. 2012, Kalyakin et al. 2014) and MASKA-LM (Sorokin and Trufanov 2017, Varseyev et al. 2014, Alekseev et al. 2015a, 2015b) codes were used. At the present time, the first 3D code version has been built for the mathematical simulation of the in-trap processes (Alekseev et al. 2017). A modified OpenFOAM code was used to address the thermal-hydraulic and mass-transport problem. The problem was solved in a steady-state definition for Reynolds-averaged Navier-Stokes (URANS) equations by the SIMPLE method.

The solution involved two stages. The fields of the coolant flow key parameters (velocity, temperature, pressure) were calculated at the initial stage. The calculation results were used at stage 2 to calculate the transport of impurities inside of the trap. To determine the temperature fields, the velocity fields, and the pressure, a thermal-hydraulic analysis was performed in a two-dimensional hexagonal grid of ~ 10 thousand hexagonal cells using a modified steady-state problem solver, *BuoyantSimpleFoam*. This included the thermophysical properties of liquid metals. The effects of buoyancy forces on the flow hydrodynamics were also included in the initial solver.

The transport of impurities inside of the trap was calculated using a rewritten solver, *TransportFoam.* The code was tested based on the obtained experimental data (Alekseev et al. 2017).

The calculations using the MASKA-LM code took into account the effects of the changes in the computational region geometry due to the deposits on the solid surfaces, which made it possible to estimate the cold trap's impurity capacity and the expiry time of the trap life.

The TURBOFLOW-based mass transport calculations for the sodium-cooled trap have shown that the coil installed near the trap wall does not change the nature of the flow but increases the cooling intensity and the circulating flow rate. The coil installed close to the trap center slows down the circulating flow. This changes the distribution of the trap wall impurity precipitation. The greatest cooling and impurity concentration reduction at the trap outlet are achieved with the coil being closer to the wall in which case the coil has the maximum surface. The effects of the inlet tube length on the trap flow characteristics are demonstrated in Fig. 4. Each individual part of the figure shows the cross-section of a half of the trap's inner space beneath the filter between the central axis and the body (see Fig. 1). The stagnant region on the trap bottom is reduced and the coolant circulation grows in intensity as the downcomer length is increased. There is no stagnant region if the downcomer is 0.9 m off the trap bottom.

The region containing a crystallized impurity is larger with the submerged tube. The impurity precipitation on the trap's inner surfaces becomes more uniform. The impurity precipitation rate also increases due to the outlet temperature reduction.

It is important to analyze the possibility for increasing the system efficiency. The key prerequisite for this is obviously to increase the trap volume while providing for the required heat removal. Since the sodium-cooled trap volume is less than 13% of the volume occupied by the entire purification system structure in the reactor tank, then there is a reserve for increasing the trap volume. For instance, it was shown that using an effective heat insulation would make it possible to reduce its thickness and to increase so the trap diameter. As shown by pre-estimates,

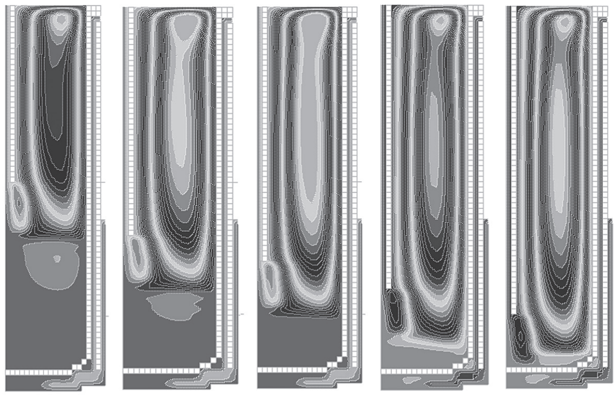

Figure 4. Pattern of the sodium flow in the cold trap with different downcomer lengths.

this alone can increase the efficiency by a factor of 1.5. Specific technical solutions require dedicated studies.

In particular, the trap capacity can be increased by 5 to 6% through optimizing the use of the filter volume (respective engineering solutions are needed). And it follows from the data on the share of the sodium oxide bulk concentration in different areas that the trap, for which the probability of the local cross-section blocking has been minimized, may have its capacity reaching 30 to 40% of the volume. These shall be probably viewed as the maximum figures requiring dedicated R&D to be achieved in a particular design.

Conclusion

A scientific rationale was developed as the result of the studies to build, jointly with OKBM and OKB Gidropress, cold traps of a unique design for the BN-350, BOR-60, and BN-600 reactors. These traps have the impurity capacity (one of the most important operating characteristics) three to five times as high as that of the best foreign counterparts. Tests have shown that the traps are efficient in purifying sodium of oxygen and hydrogen. The results of the studies were used to optimize the BOR-60, BN-350, and BN-600 trap designs. The BN-350 traps reached the end of their operating life, and the BN-600 traps have been in operation for over 35 years.

It has been shown that hydrogen will migrate into the secondary circuit traps as the temperature at the primary circuit cold trap outlet increases to 150 °C, while the previous temperature conditions of the secondary circuit trap are maintained (the secondary circuit trap outlet temperature is 120 °C), and with the total flow rate through the secondary circuit traps being over 44 m^3/h.

For the trap version cooled by argon pressurized to 1.5 MPa, the working space volume was 1.75 m^3, and the estimated impurity capacity was 350 kg. With the reactor purification system operating with three traps based on the standard flowchart, 20 trap replacements will be required during the entire reactor lifetime, and only seven replacements will be needed if the deposition of hydrogen into the primary circuit traps is excluded.

The sodium-cooled version of the trap built in the reactor tank has the same overall dimensions as the argon-cooled trap but its working space volume can be much larger reaching 1.86 m^3 and the impurity capacity can be 441 kg. Additionally, the trap is equipped with a coil. The cooling sodium circulates in two cooling trains: outside the jacketed working space body (up to 30% of the flow rate) and in the coil installed inside of the working space (up to 70% of the flow rate, in the trap initial operating period). The working space cooling by sodium instead of argon excludes the element with an increased potential energy.

Updates have been proposed to the technical solutions based on the calculations of the thermal-hydraulic and mass-transport processes in the trap using the developed codes. Recommendations have been provided for improving the design of the in-tank trap to increase its efficiency and impurity capacity. The implementation of the particular trap design requires dedicated R&D.

References

- Alekseev AA, Kozlov FA, Sorokin AP, Varseyev YeV, Kumayev VYa, Kondratyev AS (2015a) Calculation of the impurity mass transport in sodium-cooled cold traps. Proc. of the Sci. and Techn. Conference “Thermophysics of Fast-Neutron Reactors (Thermophysics 2014)”. Obninsk: SSC RF-IPPE Publ.: 380–385. [in Russian]
- Alekseev VV, Kovalev YuP, Kalyakin SG, Kozlov FA, Kumayev VYa, Kondratyev AS, Matyukhin VV, Pirogov EP, Sergeyev VV, Sorokin AP, Torbenkova IYu (2013) A sodium coolant purification system for a nuclear power plant with a BN-1200 reactor. Teploenergetika, 60(5): 311–322. https://doi.org/10.1134/S0040601513050017 [in Russian]
- Alekseev VV, Kozlov FA, Sorokin AP, Trufanov AA, Kryuchkov YeA, Varseyev YeV, Konovalov MA, Torbenkova IYu (2017) Sodium bench testing of a cold trap model. Atomnaya energiya, 122(1): 35–41. https://doi.org/10.1007/s10512-017-0232-1 [in Russian]
- Alekseev VV, Kozlov FA, Sorokin AP, Varseyev YeV, Kumayev VYa, Kondratyev AS (2015b) Calculation of the impurity mass transport in sodium-cooled cold traps. Atomnaya energiya, 118(5): 318–323. https://doi.org/10.1007/s10512-015-9999-0 [in Russian]
- Kalyakin SG, Kozlov FA, Sorokin AP, Alekseev VV, Shcherbakov SI, Kondratyev AS, Varseyev YeV (2014) Studies to justify the sodium purification system built in the reactor tank. Izvestiya vysshykh uchebnykh zavedeniy. Yadernaya energetika 2: 81–89. https://doi.org/10.26583/npe.2014.2.09 [in Russian]
- Kozlov FA, Alekseev VV, Kovalev YuP, Kumayev VYa, Matyukhin VV, Orlova YeA, Pirogov EP, Sergeyev VV, Sorokin AP, Shcherbakov SI (2012) Studies to justify a sodium purification system for fast reactors. Atomnaya energiya 112(1): 21–28. https://doi.org/10.1007/s10512-012-9519-4 [in Russian]
- Kozlov FA, Alekseev VV, Zagorulko YuI, Sergeyev GP, Volchkov LG, Kozub PS, Kovalev YuP, Vorobyeva TA, Volov AN (2007) The results of developing a technology for using sodium as the fast-neutron reactor coolant. Teploenergetika 54(12): 942–954. https://doi.org/10.1134/S0040601507120026 [in Russian]
- Kozlov FA, Volchkov LG (1975) A novel technique to regenerate traps for purification of alkaline liquid metal coolants. Atomnaya energiya 39(4): 310. https://doi.org/10.1007/BF01261913 [in Russian]
- Kozlov FA, Volchkov LG, Kuznetsov EK, Matyukhin VV (1983) Liquid Metal Coolants for Nuclear Power Plants. Purification of Impurities and Their Control. Moscow. Energoatomizdat Publ., 128 pp. [in Russian]
- Rachkov VI, Poplavskiy VM, Tsibulya AM, Bagdasarov YuYe, Vasilyev BA, Kamanin YuL, Osipov SL, Kuzavkov NG, Yershov VN, Ashirmetov MR (2010) Concept of an advanced power unit with the BN-1200 sodium-cooled fast reactor. Atomnaya energiya, 108(4): 254–259. https://doi.org/10.1007/s10512-010-9286-z [in Russian]
- Sorokin AP, Trufanov AA (2017) Sodium purification in NPPs with fast-neutron reactors. VANT. Ser. Yaderno-reaktornye konstanty, 3: 142–162. https://vant.ippe.ru/year2017/3/thermal-physics-hydrodynamics/1381-12.html [accessed Oct 04, 2019] [in Russian]
- Varseyev YeV, Konovalov MA, Alekseev VV (2014) Results of a heat and mass transport numerical simulation in a cold trap mock-up. VANT. Ser. Yaderno-reaktornye konstanty, 2: 106–113. https://vant.ippe.ru/images/pdf/2014/2-11.pdf [accessed Oct 04, 2019] [in Russian]
- Vasilyev BA, Vasyaev AV, Zverev DL, Shepelev SF, Ashirmetov MR, Yershov VN, Onufrienko SV, Goverdovskiy AA, Poplavskiy VM, Trufanov AA, Oshkanov NN (2016) An innovative design of the BN-1200 power unit as the basis for the evolutionary development of the BN series. Proc. of the 4th International Scientific and Technical Conference “Innovative Designs and Technologies of Nuclear Power (ISTC NIKIET-2016)”. Moscow. AO NIKIET Publ.: 38–40. [in Russian]