Sodium purification systems for NPP with fast reactors (retrospective and perspective views)

F.A. Kozlov[a], A.P. Sorokin[a,*], M.A. Konovalov[a,b]

[a] *JSC "SSC RF – Institute for Physics and Power Engineering n.a. A.I. Leypunsky", 1, Bondarenko Sq.,Obninsk, Kaluga Region 249033, Russia*
[b] *NRNU MEPhI, 31, Kashirskoe Shosse, Moscow 115409, Russia*

Available online 6 May 2016

Abstract

Coolant purification systems constitute integral element of any reactor facility. A number of new tasks emerge in the current day reactor engineering, one of which is the task to enhance productivity and capacity of such systems. Retrospective analysis of coolant purification systems in nuclear reactors from BR-5 to BN-1200, such as cold traps and sorbents for purification from cesium ensuring successful operation of nuclear power installations equipped with sodium-cooled fast neutron reactors and hot traps representing promising concept to be used for sodium purification from oxygen on NPPs demonstrated that there exist capabilities for enhancing characteristics of such systems. Main directions of efforts for improving characteristics of purification systems for future NPPs equipped with sodium-cooled reactors were suggested based on the results of the implemented studies. Cold trap must be included as the mandatory element of the purification system of the reactor primary cooling loop both in normal and in standby operational modes. Optimal solutions on the purification from radioactive impurities and non-radioactive corrosion products as applied to fast sodium-cooled reactors require implementation of purposeful R&D efforts.
Copyright © 2016, National Research Nuclear University MEPhI (Moscow Engineering Physics Institute). Production and hosting by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Introduction

Coolant purification systems (PS) constitute requisite element of any reactor facility (RF). Composition of the PS is determined by the values of sources and sinks of impurities in all possible modes of operation of nuclear power installation and by the requirements on the permissible concentrations of impurities. PS of NPPs operated with sodium coolant must have the following features:

- Have throughput capacity ensuring the required degree of purity of the coolant in all operational modes (normal operation mode and reactor core fuel reloading mode, scheduled and preventive repair operations, mitigation of emergency coolant contamination) during the time periods established by the technical design specifications for the reactor facility;
- Have sufficient retention capacity as pertains to impurities to minimize the number of required operations for replacement of the PS elements;
- Do not produce negative effects on the financial performance of the NPP.

Retrospective analysis of PS (in the fast reactor facilities from BR-5 to BN-1200) demonstrates that the following three main phases can be singled out from the chronological and scientific and engineering viewpoints in the development of sodium-cooled fast RF: the first phase from 1956 until 1959 (BR-5 reactor); the second phase from 1960 until 1980 (Bor-60, BN-350 and BN-600 reactors) and the third phase starting from the beginning of the third millennium until the present moment (BN-1200 reactor).

Cold traps

Practical issues of reactor design, assembling and operation with regard to BR-5 reactor and nuclear power installations for space applications [1] were addressed during the first phase. As the result of analysis the following two methods were selected among possible purification methods for implementation of subsequent R&D efforts: cold traps for NPPs and hot traps for nuclear power installations for space applications.

As pertains to the sources of impurities, the main attention was paid during the first phase to oxygen present in the ambient air contaminating sodium systems in the process of installation, repair and other operations. As of today hydrogen, carbon, corrosion products, fission products, e.g. cesium and tritium, and even the reactor fuel per se (in case of fuel pin cladding failures) are analyzed during the phase of development of design of NPP equipped with BN-1200 reactor taking into consideration almost hundred years of experience (only in this country) of operation of NPPs with sodium-cooled reactors.

Efforts aimed at the substantiation of cold trap design (CT) were started from the investigation of characteristics of the trap similar to that described in [2]. The whole effective volume of the CT was filled in the first model with fixture made of stainless steel wire. Trap was cooled with boiling toluene. It was first of all established that sodium cooling to the preset temperature is ensured with exclusion of sodium freezing in any part of the CT. Here, according to the readings of the plug indicator, sodium is purified from impurities to reach concentrations corresponding to their solubility in sodium at temperatures at the CT outlet. It was found that as pertains to these parameters development of CT for BF-5 reactor, as well as for reactor facilities of BN-350 type does not encounter any problems of principal importance.

However, CT retention capacity with regard to trapping sodium oxide amounted to only 1.5% by volume. In order to improve this performance indicator the second trap was modernized prior to its testing as follows: the wire fixture was removed from the trap inlet and settling chamber was added. As the result, CT capacity increased to reach 3% by volume [3]. It was decided to equipBR-5 reactor with traps of this type (Fig. 1a) despite the unsatisfactory CT capacity performance. Afterwards this factor played negative role in reactor operation: 16 CT units of the primary cooling loop were replaced.

During the second phase theoretical, numerical and experimental studies of thermal hydraulic and mass exchange processes were undertaken as part of the development of high-capacity CT for BN-350, BOR-60 and BN-600 reactors both using specially designed experimental sections and on CT units. Implementation of these studies can be divided into the following two periods: until the beginning of the 1970-ies when R&D was conducted for substatiation of CT design for BN-350 and BOR-60 reactors, and the following phase until the end of the 1970-ies when R&D efforts were directed towards substatiation of CT design for BN-600 re-

actor(it was originally accepted that CT of the primary cooling loop will be nitrogen-cooled). Experimental sections were used in the studies until 1970 where forced and natural convection flows inside the circulation area had the same direction – i.e. this was parallel mixed convection flow (PMCF). After that sodium penetrated the isothermal settling chamber and then the filter.

It was established that sedimentation of oxide within the cooling area begins practically immediately, as soon as the solution becomes oversaturated. This factor is the main reason of the limited CT trapping capacity, because local blocking of flow cross-section takes place. Values characterizing distribution of oxide within the cooling area obtained according to the results of analysis and those calculated in the assumption that sodium oxide crystallizes from the oversaturated solution only on immobile surfaces washed by sodium, and conditions of samples in the presence of the fixture after distillation of sodium from them are presented in Fig. 2a (similar results were obtained without the fixture as well). It is clear from the figure that the distributions significantly differed from each other. Assumption was made that the most probable cause of this discrepancy between the calculated and the experimentally determined quantities of oxide within the cooling area amounted to the fact that beside crystallization on immobile surfaces crystallization from the oversaturated solution also takes place on the crystals present in the sodium solution. Calculations demonstrated that contributions from these two effects can reach significant values.

In case of small accumulated quantities concentrations of oxides in the isothermal settlement chamber decrease with increased distance from the bottom; with increasing accumulated quantities concentration is first maintained at a certain average level (approximately equal to the concentration near the bottom of the settlement chamber) and then begins to decrease. Retention of oxides in the settlement chamber amounts to 11 and 46% with chamber length equal to 0.3 and 0.85 m, respectively. It has to be noted that in the experiments with high retention of oxides within the cooling area higher retention of oxides within the settlement chamber was obtained as well (~32% with chamber length equal to 0.3 m).

It follows from theoretical analysis that distribution of oxides in the isothermal filter must exponentially decrease with increased distance from the inlet. Within the limits of scatter of experimental data C_i/C_{in} until the distances from the inlet equal to $(3-4)$ $l_{0.5}$this effect actually takes place. At larger distances decrease becomes slower. Increase of $l_{0.5}$with increased velocity in laminar mode of flow around the fixture and practically constant values within the investigated range of velocities in the turbulent flow mode were obtained in the experiments. Such dependence of $l_{0.5}$ in the isothermal filter on the sodium flow velocity is understandable if it is taken into account that in laminar flow mode mass exchange coefficient increases in direct proportion to sodium velocity in the filter (velocity of sodium flow washing the fixture) $W^{0.5}$, an in turbulent flow mode it is proportional to $W^{0.9}$ [4]. It is important for the subsequent filter optimization that both in our experiments and in the CT design the fixture made