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Investigations for the substantiation of high-temperature nuclear power generation technology using fast sodium-cooled reactor for hydrogen production and other innovative applications (Part 1)

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Abstract

Neutronics and thermal physics studies of BN-VT reactor installation with 600-MW thermal power demonstrated the possibility in principle to achieve the required parameters of high-temperature fast reactor for production of large quantities of hydrogen on the basis, for instance, of one of thermal chemical cycles or high-temperature hydrolysis with high thermal efficiency of use of electric power. Relatively small dimensions, the type of coolant, selection of fissile material and structural materials allow developing nuclear reactor with particular inherent properties (exclusion of prompt-neutron reactor power excursions, removal of decay heat in passive mode) while ensuring enhanced nuclear and radiation safety.

Composition of BN-VT reactor facility includes sodium-cooled fast reactor, three cooling loops for emergency heat removal and three sets of equipment of the secondary cooling loop for heat transfer from the reactor to chemical installations generating hydrogen or to gas-turbine plant for supplying chemical equipment with electric power. Composition of each of the cooling loops includes intermediate heat exchanger arranged inside the reactor vessel, centrifugal pump and pipeline for removal and re-introduction of sodium in the reactor core. Contemporary requirements on the safety and financial performance of future generations of nuclear reactors were taken into consideration in the development of the reactor under study. Implemented calculation studies demonstrated that penetration of hydrogen within the limits of permissible allowances produce practically no effect on the neutronics and safety parameters of the reactor. Solution of the problem of fuel pin stability was mitigated due to the selection of low thermal load on fuel pins. Application of EP-912-VD steel as a possible optional structural material was examined.

Continued studies of heat-resistant materials and their behavior under irradiation are required.

Keywords: Fast reactor; High-temperature, Sodium; Hydrogen production; Pool-type configuration; Neutronics; Thermal physics; Safety issues; Steels.

Introduction

Nuclear power generation is not an alternative or a competitor within the general strategy of development of the fuel and power generation complex of the country, but, instead, it offers additional potential of preservation of efficiency of available fuel resources during extended periods of time and possibility to enhance reliability and safety of power supply becoming “the source of the source” of power and other re-

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sources. Several alternative strategies of development of nuclear power generation are currently under discussion [1,2]. One of the main requirements to future nuclear power generation technology – its large scale – implies enhanced level of safety of all its elements including reactor facilities and application of technologies of closed nuclear fuel cycle [3,4]. Development of innovative fast reactors with stressful temperature and dose rate loads with application of sodium as a coolant constitutes important direction of formation of the new technological platform [5,6].

The most significant problem determining future development of environmentally clean power generation is the inclusion of hydrogen in the fuel cycle. Hydrogen is a very attractive element as the replacement of oil and gas although by itself it is not a source but, instead, a carrier of energy. It is anticipated that the need in hydrogen production will be sharply increased in the nearest future. Currently the main method of hydrogen production is the methane reforming with steam. However, from the viewpoint of long-term perspective of large-scale hydrogen production, the above method is not viable since it requires consumption of non-renewable hydrocarbon resources and is accompanied with emission of greenhouse gases in the environment. That is why alternative methods of production of hydrogen with application of water splitting methods using thermal chemistry or electrolysis processes requiring high-temperature source of heat for enhancement of efficiency of the above processes are investigated [7,8].

Due to the application of such coolants as gases and liquid metals (sodium, lead) Generation IV nuclear reactors can serve as such sources of high-temperature heat [9,10]. Coolant temperature at the outlet of the core of such reactors can reach 900–950°C. This is a new class of nuclear reactors designed for both ensuring electric power generation with enhanced thermal efficiency (50%), and, as well, for the supporting the technological processes during hydrogen production, coal gasification and liquefaction, advanced oil cracking, conversion of biomass into liquid fuel, in chemical industry, metallurgy, etc.

Expenditure of energy is, without any doubt, needed for supporting such technological processes, but, as the result, the fuel obtained (using the example of hydrogen) possesses completely new quality allowing resolving numerous environmental problems.

Conceptual studies on the selection of the general outlook of high-temperature sodium-cooled fast power reactor (BN-VT) for large-scale nuclear and hydrogen power generation implemented at the AAC RF-IPPE under the supervision of V.M. Poplavsky demonstrated that [11] designing such nuclear reactor is a realistic task. Examination of existing reactors for the purpose of use of heat generated in them for the above described purposes is also attractive along with development of dedicated nuclear reactors for producing hydrogen. In that case heating of reactor coolant in separate loop to the required temperature must be implemented using electricity produced by such reactor. Such study was performed by the group of authors (Khorasanov et al.) on the basis of BN-600

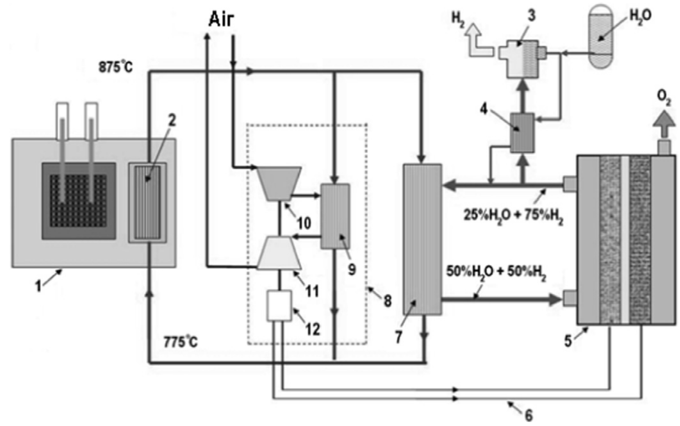

Fig. 1. Schematic layout of reactor facility for production of electricity and hydrogen on the basis of technology of solid oxide water electrolysis: 1 – fast reactor; 2 – intermediate heat exchanger; 3 – hydrogen separator; 4 – heat exchanger; 5 – solid oxide electrolysis cell; 6 – electrical power supply to the electrolysis cell; 7 – steam generator; 8 – gas turbine plant; 9 – heat exchanger; 10 – compressor; 11 – turbine; 12 – electrical generator.

reactor [12,13]. Addressing the issues of purely technological nature associated with high levels of temperature in the reactor facility (RF) becomes the first priority including the development of sodium coolant technology at elevated temperatures and high hydrogen concentrations during extended lifecycle, application of heat resistant and radiation resistant structural materials, ensuring corrosion resistance of such materials at oxygen concentrations present in sodium coolant at the level of 0.1 ppm becomes the first priority [14]. Discussion of complex (not only neutronics, but thermal hydraulics and technological) studies for substantiation of conceptual design and safety of 600-MW-th BN-VT high-temperature sodium-cooled reactor for production of hydrogen is the objective of the present paper.

Composition and techical characteristics of the BN-VT reactor facility

BN-VT reactor facility

Composition of BN-VT RF (Fig. 1) includes sodium-cooled fast reactor, three cooling loops of the emergency heat removal system, three sets of equipment of secondary cooling loops for transfer of high-potential heat from the reactor to hydrogen producing chemical installations or to gas-turbine plant intended for supplying electricity to chemical equipment. Each of the loops contains intermediate heat exchanger incorporated in the reactor vessel, centrifugal pump and pipeline for removal and re-introduction of sodium in the reactor.

Existing requirements on the safety and financial performance of reactors of new generations were taken into consideration in outlining the general configuration of the reactor under study. Innovative ideology of fast reactor on the basis of achievements and success of sodium-cooled fast reactor technology is further developed in it. BN-600 reactor successfully operated already during more than 30 years was chosen