

CONFERENCE PRE-PRINT**STATUS OF THE DEVELOPMENT OF A TRITIUM FUEL CYCLE FOR LONG-TERM TOKAMAK OPERATION**

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The paper describes the current state of development of the steady-state fuel cycle design for a tokamak as applied to fusion neutron source projects. These projects involve neutron generation at a fusion power of 3 to 40 MW via beam injection (NBI). The fuel cycle design provides fuel injection into plasma with a given isotopic composition and in the required quantity. The proposed design of the fuel cycle for a fusion neutron source ensures the operation of the DEMO-FNS and FNS-ST tokamaks with given values of plasma density and its isotopic composition in a steady-state mode. The SOLPS, ASTRA, and FC-FNS codes are used for interaction of the FC with the plasma of the core and the divertor. The range of operating parameters of the core plasma is found, in which the tritium fraction is regulated by injecting pellets with different isotopic compositions T/D. For the candidate fuel cycle technologies selected on the basis of the conducted simulation and analysis, an analysis of the technology readiness levels is carried out. The tritium and deuterium amount calculation in the facility's FC systems was carried out taking into account specific technological solutions. A roadmap for the development of tritium fuel cycle technologies has been developed, which will be implemented within the framework of the federal program of the Russian Federation "New Nuclear and Energy Technologies".

1. INTRODUCTION

Controlled fusion reactors (CFR) and hybrid reactor facilities (HRF) based on tokamaks are currently being actively developed, combining thermonuclear fusion and fission technologies. They can be in demand as promising sources of neutrons, thermal and electrical energy, as well as fuel nuclides for nuclear power reactors. At the stage of technical design, it is necessary to estimate the amount of fuel for starting facilities and formulate requirements for them [1, 2]. In addition, before the construction and power start-up of the facility, it is necessary to formulate requirements for auxiliary subsystems. These include complexes for injection, pumping, processing and storing gases, monitoring technological systems and ensuring safety when handling hydrogen isotopes, including tritium.

During plasma discharges, the parameters (including particle concentration profiles and plasma isotopic composition) necessary for the implementation of thermonuclear reactions and neutron generation conditions are provided by injection of fuel particles into a vacuum vessel. Diffusion losses from the plasma and small cross-sections of interaction of fuel components lead to high values of injected fluxes. In this case, only a part of the fuel enters the plasma, and most of the particles do not penetrate through the separatrix and enter the pumping system. In existing experimental tokamaks, the ratio of the number of fuel particles injected into the vacuum vessel to the number of particles that have entered into a fusion reaction is $\sim 10^4$. For promising projects, an additional increase of up to 10 is expected, which is primarily determined by the conditions on the divertor targets and the first wall at high fluxes of particle and heat from the plasma. According to estimates [1], the creation of an energy-efficient fusion reactor will require a reduction in this indicator. Otherwise, the fuel flows will be so large that their processing will become impossible, and the amount of tritium in the facility will reach tens of kilograms.

Coordination of fuel and gas injection processes together with the processes occurring in the core and divertor plasmas, as well as technological systems, is necessary to ensure the conditions for fusion and neutron generation. This is especially true for facilities with a steady-state operation. The efficiency of particle feeding depends on the method of their introduction into the plasma. Along with gas injection into a vacuum vessel, which has the lowest plasma supply efficiency, injection of fast atoms in the form of heating (neutral) beams is used, as well as injection of frozen fuel pellets. The latter two methods have the highest efficiency, but the

particle flow in the beams is limited by the additional heating capacity. As a result, fuel pellet injection remains the key way to effectively control plasma parameters during the discharge [2]. The processes in the core plasma are accompanied by regular and pulsed losses of particles and energy, which leads to the emergence of various processes in the wall region and the divertor.

The systems providing injection of particles, their pumping, processing and storage of gas form a closed fuel cycle (FC) of the facility. In addition to providing plasma parameters, the FC system must maintain vacuum conditions in the facility and circulation of fuel components and auxiliary gases with their controlled emission into the atmosphere. For economic and environmental reasons, the FC should be closed [1-3].

To date, the world has accumulated extensive experience in working with tritium in laboratories and in various physical facilities. CFR tritium systems with a tritium reserve of up to 70 g have been created and successfully operated on TFTR and JET tokamaks. In recent years, the efforts of the world international community have been focused on designing the FC of the ITER; prototypes of all the main FC systems for the national CFEDR project have been created in China [4]. Meanwhile, the creation of reactors with long-term or stationary discharges requires a fundamentally new approach to the organization of the FC and the use of new technological solutions for its systems, since all facilities currently operating and those being designed have implemented a pulse-periodic mode in which the gas mixture is processed during the breaks between discharges. The transition to long-term pulses will require stationary operation of all FC systems with the coordination of operating modes and flows. At the same time, the total amount of tritium in the facility site should be reduced as much as possible. The creation of stationary installations with a fuel cycle similar to existing experimental installations will lead to an unjustified accumulation of tritium in the systems. The experience of organizing tritium FCs of modern tokamaks can only be partially used, since tritium handling technologies can be scalable with significant limitations, and the work of a stationary fuel cycle will require the use of new technologies and additional research on their integration [5].

Tritium artificially produced in fission reactors will be required for fusion reactor startup and operation. Global reserves of commercially available tritium are limited and amount to less than 30 kg. A CFR with fusion power 1-3 GW, comparable to fission reactors, will burn up 50 to 150 kg of tritium per year. For this reason, the facility must produce tritium in a breeding blanket. For a fusion neutron source (FNS) or HRF tritium breeding requirements can be significantly reduced due to a smaller facility capacity and different target products (and therefore a different scheme for closing the nuclide and energy balance). Meanwhile, FNS and HRF can contain a tritium-breeding blanket and the fuel cycle can process it.

A system analysis of tritium fuel cycle systems for stationary fusion neutron source projects was carried out in the Russian Federation. According to the authors, the developed approach to organizing a fuel cycle can be considered as a general case, and solutions for specific projects (including experimental and educational facilities) will be special cases.

2. DEVELOPMENT OF A STATIONARY FUEL CYCLE MODEL

To date, the fuel cycles of all tokamaks, including those using tritium, have been built with a minimum of systems and complexities. Unfortunately, this approach cannot be applied to the fuel cycles under construction and prospective CFRs [1, 2]. Figure 1 shows a diagram of the main systems providing a steady-state tokamak fuel cycle. It can be divided into 3 functional circuits, the first circuit is designed for rapid processing of tokamak exhaust gases. The second circuit is designed to separate tritium from the reactor Li-blanket (if any). The third circuit is to process tritium-containing waste, as well as to separate tritium from flows (including from the air of working rooms in the event of an accident) and to separate auxiliary gases. The last circuit is represented by a tritium-containing gas processing system, which combines the processing of gases from the first circuit of the fuel cycle with trace amounts of tritium, as well as emergency processing and cleaning of the atmosphere of rooms and boxes with equipment. This structure is typical for most conceptual and designed reactors with the tritium production function (in the absence of a blanket, the FC of the facilities has two loops). The design with three loops is complicated by the fact that the composition of the flow from the blanket differs significantly from the gases of other loops and it is impractical to mix them. For facilities with pulsed plasma discharges, in which full-scale reproduction of tritium is not planned, this problem is solved in a tritium plant, ensuring the processing of all gases during the time between pulses. For the CFEDR and DEMO-FNS projects, which assume tritium reproduction in a blanket to fully provide the installation with fuel, a third loop in the FC is typical.

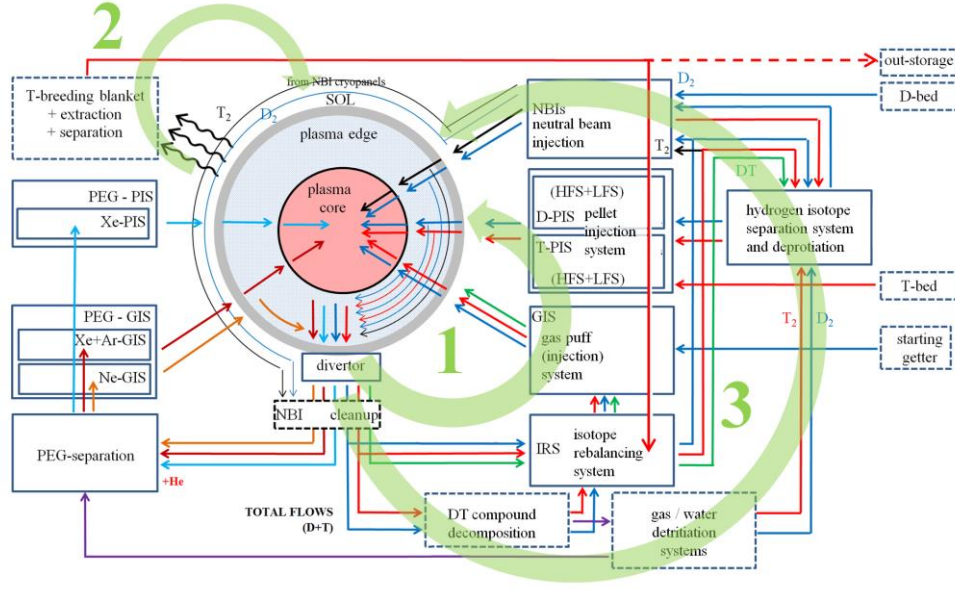


FIG. 1 Tokamak fuel cycle systems scheme. The colored arrows in the figure show the fuel components flows

In order to reduce tritium inventories at the facility site, it is advisable to organize several circuits (it can be considered that the existing tokamak FCs with a pulse-periodic operating mode has one circuit, and for prospective CFRs, the FC is designed with three circuits and an operational storage facility). The principle of organizing the main FC circuits is that each circuit contains systems with comparable gas processing times. In this case, flows with a lower tritium inventory should circulate in the circuit containing systems with a longer processing time, and vice versa - flows with the highest tritium inventory are processed by systems with a minimum gas residence time in them [6, 7]. Thus, there is a reduction in flows with a high tritium concentration and a reduction in the processing time, and these measures together ensure a reduction in the tritium inventory at the facility. In Fig. 2, the inner and outer circuits are conventionally indicated by arrows.

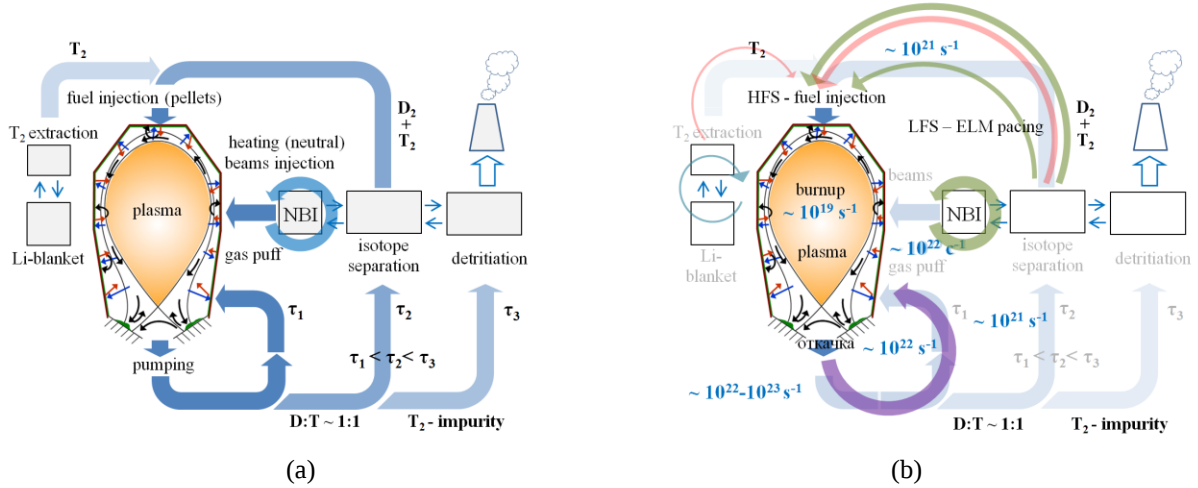


FIG. 2 Organization of several circuits in the fuel cycle. (a) conceptual diagram and (b) taking into account different flow sizes and its isotopic composition (shown in colors)

In the diagram shown in Fig. 2(a), the FC includes the gas cleaning and gas injection loops, separation and fuel injection, gas and atmosphere detritiation, gas supply to the beam injectors, and tritium extraction from the blanket. With extended tritium production in the breeding blanket (including for the HRF), its excess will be accumulated in long-term storage. Regardless of tritium breeding ratio in blanket, tritium will be consumed as fuel by the fueling systems. In all cases, the flows are stationary, the FC design does not include an operational storage facility that accumulates gases after their processing and before discharge, and the FC systems are

coordinated in terms of gas processing time, flows, and their isotopic composition. Fig. 2(b) shows 13 gas processing loops with different isotopic compositions, different tasks, and different technologies used. Such a structure of the FC systems ensures the minimum possible tritium inventory in a stationary operating facility.

The particle flows in the fuel cycle are determined primarily by the requirements for the plasma parameters provided by the injection systems, as well as by the flows in the pumping system coming from the vacuum vessel to the control systems [1, 2]. Therefore, the modeling of FC systems and the calculation of the particle flux should be related to the models of core plasma and divertor plasmas. Computer codes used for modeling plasma discharges, vacuum pumping, processes within gas mixture components, etc., are designed to solve local problems and are most often not integrated to perform consistent calculations. System codes suitable for modeling steady-state scenarios of the facility operation operate with a simplified plasma model and rarely take into account the processes inside the vacuum vessel, except for thermonuclear burning. Modeling of fuel cycle systems with the interaction of the core and divertor plasmas can be implemented using the SOLPS, ASTRA and FC-FNS codes, as was done in [8-11]. The fuel cycle simulation is performed using the FC-FNS code toolkit [11, 12].

This code was created and tested for stationary fusion neutron sources based on tokamaks (RF projects FNS-ST and DEMO-FNS) [13]. The range of operating parameters for the core plasma was determined, in which the tritium fraction is regulated by injection of pellets with different isotopic compositions T/D (separate injection of D and T pellets). The influence of heating and neutral beam feed (500 keV/30 MW beams for the DEMO-FNS/40 MW fusion power and 130-200 keV/5-10 MW beams for FNS-ST/3 MW with D/T/D+T composition), as well as due to recirculation and supply of neutral particles from the divertor [12] were also taken into account. The plasma was investigated and the effect of HFS and LFS pellet injection on its feed and ELM pacing was considered. A method for calculating hydrogen isotope fluxes in plasma and the D-T fuel cycle was developed taking into account the plasma discharge parameters [10, 14]. The technical characteristics of the FNS fuel cycle systems and the selected technologies were determined. Taking into account the gas flows and isotopic composition in the systems, as well as the technologies selected taking into account their technical characteristics, the mutual integration of the technological systems and the smallest tritium inventory in them were determined [15, 16]. The tritium and deuterium inventories in the fuel cycle systems were calculated using a computer model of the systems taking into account the technologies used and the design features of the tokamak and technological systems [12, 17]. The structural diagram of the FC systems used in the FC-FNS code is shown in Fig. 3. The code allows simulating various scenarios of gas supply to neutral injectors, which was done for the FNS-ST and DEMO-FNS projects. It has been shown that in order to increase the neutron yield in the FNS-ST project it is advisable to inject T-beams into D-plasma with complete separation of the gas pumped out of the vacuum vessel [12].

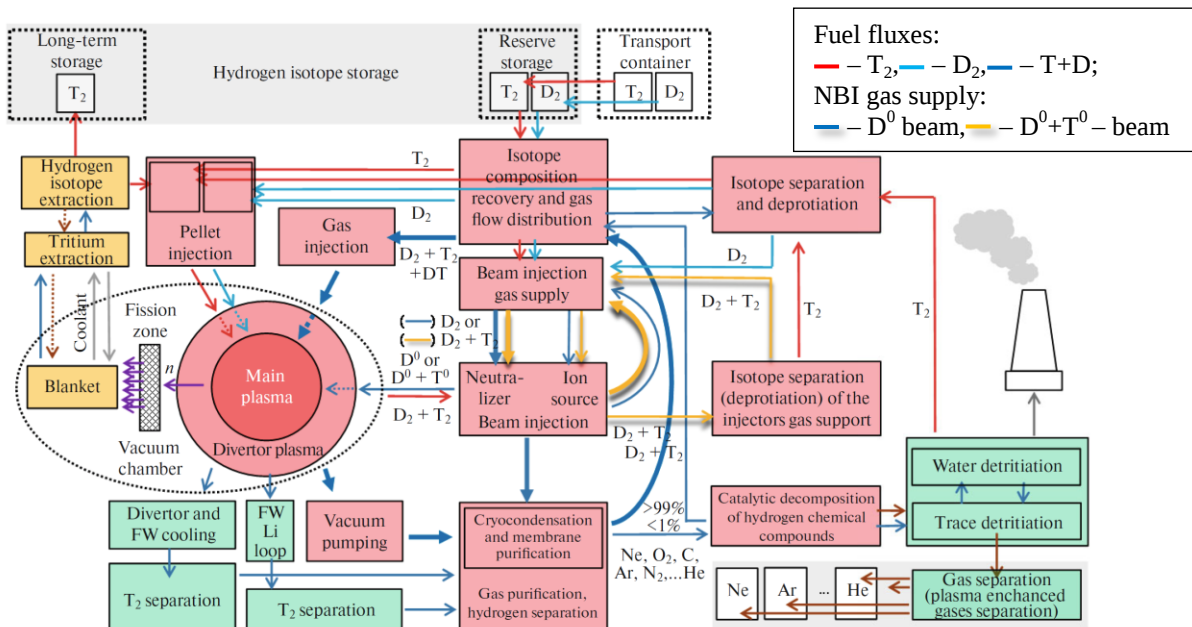


FIG.3. Block diagram of fuel cycle systems. Main circuits are divided by colors: ■ – fast processing of the tokamak exhaust, ■ – tritium extraction from the blanket, ■ – processing of tritium-containing waste.

As a result of the optimization of the D-T facility (FNS as an example) steady-state fuel cycle, a design of systems with gas processing in the “real time” mode without accumulation in operational storage facility was proposed (see FIGs 1, 3). The reduction of gas flows and quantities is achieved due to several separate loops with DT fuel (for each of which the gas composition and its flow are substantiated and mathematically described). This made it possible to reduce the tritium inventory required for the start-up and operation of the facilities (less than 0.5 kg for DEMO-FNS/power of 40 MW and less than 0.1 kg for FNS-ST/power of 3 MW) by up to 10 times compared to estimates from simple models [16-18]. An important feature of the described approach is that it allows linking the plasma discharge parameters with candidate/applied fuel cycle technologies.

3. READINESS LEVEL ANALYSIS OF TRITIUM FUEL CYCLE TECHNOLOGIES

Based on the results of the FC modeling, candidate technologies for the steady-state tokamak fuel cycle (applicable to the FNS projects in the Russian Federation) were selected [14, 15] and an analysis of the technology readiness levels was performed [19-21]. The results of the analysis are shown in TABLE 1. The general conclusions from the analysis of the availability of tritium fuel cycle technologies can be formulated as follows:

- Russian Federation has a significant reserve in various areas of tritium and related technologies application, which is formed thanks to: the experience gained in the military sphere, the use of tritium for civilian purposes, work within the framework of international projects (based on ITER and hybrid systems), as well as fundamental research using tritium;
- The readiness of tritium fuel cycle technologies is currently insufficient for application in the FC of FNS projects. Most of the considered technologies are at the development stage TRL 4-6, and their further development requires significant organizational efforts and financial support for scientific and design teams;
- To test the technologies in conditions close to real-world operating conditions, integrate technologies, and substantiate reliability and safety, it is necessary to create large-scale experimental stands and/or small-sized thermonuclear installations designed to work with tritium;
- A higher readiness level of most of the analyzed technologies in the world, as well as the import of individual technologies, makes international cooperation in this area attractive.

TABLE 1. TECHNOLOGY READINESS LEVEL OF A SSO-TOKAMAK TRITIUM FUEL CYCLE [21]

Process	1	2	3	4	5	6	7	8	9
Membrane separation	■	■	■	■	■	■			
Hydrogen isotopes chromatographic and cryogenic separation	■	■	■	■	■	■	■		
Chemical isotope exchange (CECE)	■	■	■	■	■				
Adsorption at temperature N ₂ (liquid)	■	■	■	■	■				
Phase isotope exchange in scrubber	■	■	■	■	■	■			
Sorption storage of tritium	■	■	■	■	■	■	■		
Ceramic materials for blanket	■	■	■	■	■				
Liquid metals for blanket	■	■	■	■	■	■			
Tritium extraction from blanket	■	■	■	■	■	■			
Injection of neutral particles	■	■	■	■	■	■	■		
Pellet injection	■	■	■	■	■	■			
Gas injection	■	■	■	■	■	■	■		
Tokamak VV pumping (exhaust)	■	■	■	■	■	■	■		
Multilevel protection	■	■	■	■	■	■	■		
Analysis of tritium and its compounds	■	■	■	■	■	■	■		
Tritium capture and recycling	■	■	■	■	■	■	■		
Tokamak VV materials (PFM, SM)	■	■	■	■	■	■	■		
Materials for working with tritium	■	■	■	■	■	■	■		

(■) Russia now; (■) Russia in the future; (■) world now; (■) world in the future.

It is worth paying special attention not only to the need to improve the level of technologies for handling tritium, but also to increase the level of staff training, as well as to increase the total number of engineering, technical and scientific personnel in this industry.

For specific best technology solutions for the fuel cycle systems, the computer model in the FC-FNS code was modified (code modules describing specific systems have simulated operation taking into account physical and chemical mechanisms, input and output flows, etc., to best match the selected technological process). This made it possible to increase the accuracy of calculating the fuel components inventory, including tritium, in the FC systems [16]. It should be noted that similar logic and methodology for calculating the tritium inventory are used within the EU-DEMO project [6]. The tritium inventory in the fuel cycle systems of the FNS projects for different scenarios/compositions of heating beams are shown in TABLE 2. Italics show (for FNS projects) values calculated using standard fuel cycle models [1, 18]. This illustrates the shortcomings of models that do not take into account the current FC system design, technologies used, and processes inside the tokamak vessel.

TABLE 2. TRITIUM INVENTORIES IN FUEL CYCLE SYSTEMS FOR DIFFERENT SCENARIOS OF HEAT BEAM (GAS ISOTOPE COMPOSITIONS). ITALICS SHOW VALUES CALCULATED USING STANDARD FC MODELS [1, 18].

Fuel cycle systems	FNS-ST, (g)		DEMO-FNS, (g)		ITER, (g)	EU-DEMO, (g)
	<i>D+T-beam</i>	<i>D / T-beam</i>	<i>D+T-beam</i>	<i>D-beam</i>		
Gas puff injection		15 / 0		45	10	421
Pellet injection	-	25 / 0	-	50	45	
Beam injection		1 / 40		8	1	-
Vacuum vessel and PFC	-	8	-	20	1000 lim	-
Tokamak pumping	<i>450</i>	10 / 2	<i>4500</i>	60	170	80
Gas separation		1		2	30	6
Hydrogen compounds catalytic decomposition	<i>10</i>	8 / 1	<i>100</i>	10	10	11
NBI gas composition control	-	1 / 2	-	1	-	-
Isotope separation	<i>40</i>	22 / 15	<i>450</i>	80-150	< 250	550+600
Gas pipelines, receivers	-	115 / 15	-	70	200	-
Start-up/backup storage	<i>600/-</i>	4 / 2	<i>5300/-</i>	120	< 450	-
Blanket, tritium separation	2	2	<i>130</i>	2	-	~ 70
Total inventory	<i>600</i>	210 / 90	<i>5300</i>	500	4000	1800

Such a roadmap of tritium fuel cycle technologies was developed, and a draft design of laboratory stands for testing the main technological processes in the interests of the FC was developed. The roadmap is shown in FIG. 4. Each stage contains an activities structure aimed at achieving milestones. The technology development program envisions several stages for creating a functioning fuel cycle system within the tokamak complex:

1. Creation of a set of laboratory mockups for research and improvement of individual fuel cycle systems (systems based on new physical principles with improved characteristics). The creation of such facilities is not mandatory, but is highly desirable for training scientific personnel and improving the overall system's performance.
2. Creation of a tritium-free protium-deuterium fuel cycle, testing, and endurance testing of all fuel cycle systems during joint operation. This system can be created at any site; proximity to the tokamak is not required.
3. Creation of a tritium fuel cycle with a relevant amount of tritium. This system can be created at any site with permission and experience working with large amounts of tritium.
4. Creation of a tritium fuel cycle system at the tokamak.

Implementing Stage 4 without completing Stages 2 and 3 carries significant risks associated with the complexity of the fuel cycle system, the need for preliminary system development and endurance testing, technology optimization, etc. Meanwhile, to verify the results and validate the simulation models, it is advisable to create a closed fuel cycle without tritium in the tritium-free tokamak system. Operating the tokamak with an H-D fuel mixture will enable testing of the main systems of the fuel cycle without using tritium as a fuel component.

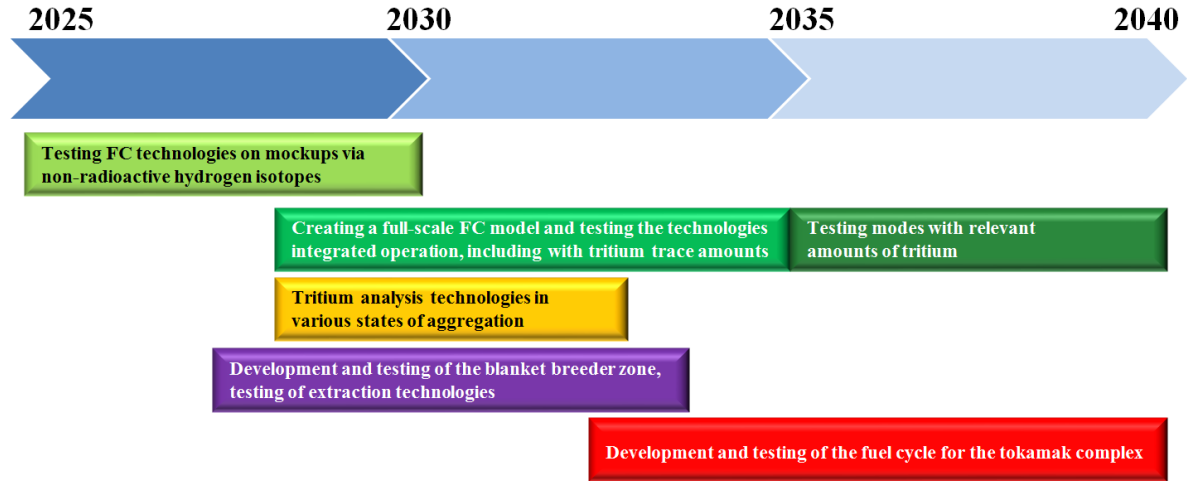


FIG. 4 Roadmap of tritium fuel cycle technologies development

As preparatory procedures technical specifications were prepared for the design of a complex of laboratory stands for working with non-radioactive hydrogen isotopes and trace amounts of tritium, as well as for a closed FC model with the main technological processes and systems and research with significant tritium inventory (relevant gas mixtures). A tritium complex design was prepared for conducting comprehensive research within the framework of national programs on thermonuclear science and nuclear technology. This infrastructure could allow for research using tritium and ensure timely training of scientific and technical personnel, as well as an increasing the level of technological readiness.

CONCLUSION

A concept for implementing a steady-state DT fuel cycle for tokamak-based fusion neutron sources has been developed in the Russian Federation. The FC-FNS code has been created and it is used to simulate the fuel cycle operation. Modeling the FC systems operation and calculating the fuel particle flows should be related to the core plasma parameters and divertor modes. For this purpose, a combination of improved SOLPS, ASTRA and FC-FNS codes are used, taking into account the interaction of gas flows with plasma. The influence of specific gas mixture flows on plasma optimization and minimization of tritium inventory at the site for the FNS-ST (3 MW) and DEMO-FNS (40 MW) projects was studied in detail.

Being based on the results of the simulation, candidate technologies for the stationary tokamak fuel cycle were selected and the technology availability levels were defined. The reserves of tritium and deuterium in the FC plant's systems were evaluated taking into account specific technological solutions that have been selected as the best for the fuel cycle of the FNS-ST and DEMO-FNS projects. An improved A novel computer model in frames of the FC-FNS code has improved the accuracy of calculating fuel component reserves. The developed design of the fuel cycle for a thermonuclear neutron source makes it possible to ensure the operation of the DEMO-FNS and FNS-ST tokamaks in a stationary mode with pre-set plasma density and isotopic composition.

Dividing the fuel cycle of a thermonuclear neutron source into several fuel circuits (from 5 to 13) ensures a minimum supply of tritium in the fuel cycle (less than 0.5 kg for the DEMO-FNS/40 MW project and less than 0.1 kg for the FNS-ST/3 MW project). The reduction of tritium reserves at the DEMO-FNS installation (40 MW) was achieved by closed loop gas support for monoisotopic deuterium heating beams (NBI). Separately supplying fuel pellets of deuterium and tritium as well as puffing a gas mixture with the isotopic composition of the gas pumped out of the tokamak without separating into isotopes [10, 16] reduced tritium flows in the fuel cycle while maintaining the integral gas flow through the tokamak vacuum vessel. This reduced a tritium inventory in the systems. The use of monoisotopic beams of tritium atoms (NBI) for heating deuterium plasma in the FNS-ST project (3 MW) makes it possible to minimize tritium reserves at the plant due to its absence in

the pellet injection system and in gas pipelines [12]. The proposed design of the fuel cycle of a thermonuclear neutron source makes it possible to ensure the operation of the DEMO-FNS and FNS-ST tokamaks with preset plasma density and isotopic composition in a stationary mode.

It is shown that the readiness of tritium fuel cycle technologies in the Russian Federation is insufficient for using in the FC of FNS projects. Most of the considered technologies are at the development stage TRL 4-6, and their further development requires significant organizational efforts and financial support for scientific and design teams. To test the technologies in conditions close to those of real operation, integrate technologies, and justify reliability and safety, it is necessary to create large-scale experimental stands and/or small-scale fusion facilities designed to work with tritium. Such a roadmap of tritium fuel cycle technologies was developed, and a draft design of laboratory stands for testing the main technological processes in the interests of the FC was developed. Technical specifications were prepared for the design of a complex of laboratory stands for working with non-radioactive hydrogen isotopes and trace amounts of tritium, as well as for a closed FC model with the main technological processes and systems and research with significant tritium inventory (relevant gas mixtures). A tritium complex design was prepared for conducting comprehensive research within the framework of national programs on thermonuclear science and nuclear technology. This infrastructure could allow for research using tritium and ensure timely training of scientific and technical personnel, as well as an increasing the level of technological readiness.

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