DEVELOPMENT AND INTEGRATION STUDY OF FUSION-FISSION HYBRID SYSTEMS INTO NUCLEAR POWER FUEL CYCLE

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Abstract

The unification of nuclear fusion and fission reactions in a single design will make it possible to achieve fundamentally new characteristics and parameters of the nuclear energy system. Development of the fusion-fission hybrid facility based on superconducting tokamak DEMO-FNS continues in Russia for integrated commissioning of steady-state and nuclear technologies at the power level up to 40 MW for fusion and 400 MW for fission reactions. Such a facility could provide burning the minor actinides accumulated by Russian nuclear fuel cycle during the operation of nuclear power plants in the future. This paper presents contemporary achievements in design and describes operation scenarios for the DEMO-FNS facility. This activity is included in the started State Research Program of Russia in the field of nuclear power.

1. INTRODUCTION

Transition to a closed nuclear fuel cycle supporting operation of thermal and fast power reactors is being carried out in Russia at the present time. In this regard, it is important to develop novel technologies for of spent nuclear fuel management and radioactive waste incineration, as well as to develop energy valuable "fusion-fission" hybrid systems. Combining nuclear fusion and fission reactions in a single design will allow achieving fundamentally new characteristics and parameters of the nuclear energy system. Development of the fusion-fission hybrid facility based on superconducting tokamak DEMO-FNS [1-3] continues in Russia for integrated commissioning of steady-state and nuclear technologies at the fusion power level up to 40 MW (more than 10^{19} neutrons per second) and 400 MW of fission reactions. This activity is included in the started state research program of Russia in the field of nuclear power.

The project aims at achieving the steady-state operation of the facility with the 14 MeV neutron wall load of ~ 0.2 MW/m^2 and the neutron fluence over the life cycle of ~ 2 $MW{\cdot}year/m^2$, with the subcritical active core for minor actinides transmutation and the fissile nuclides and tritium production blanket surfaces of ~ 100 m^2. This is sufficient for testing materials and components in the spectrum of DT thermonuclear neutrons, as well as for energy production, transmutation technology, production of fission fuel nuclides and tritium.

The analysis of the interaction of the DEMO-FNS facility and further industrial options with the nuclear fuel cycle of nuclear energy is carried out. Such a facility could provide in the future burning the minor actinides accumulated by Russian nuclear energy fuel cycle during the operation of nuclear power plants. Returning the spent fuel to a closed fuel cycle after enrichment in a hybrid industrial facility will reduce the number of nuclear fuel storage facilities and the generated radiotoxicity. This paper presents last achievements in design (2019-2020) and describes operation scenarios for the DEMO-FNS facility.

Plasma parameters the DEMO-FNS tokamak are the following.

- Plasma current IP, MA	5
- Major plasma radius R_0, m	3.2
- Minor radius of plasma a, m	1.0
- Aspect ratio R / a	3.2
- Plasma elongation k_x / k_{95}	2.0 / 1.9
- Triangularity x	0.2 - 0.5

Power parameters are presented below

- D-T fusion power	40	MW
- Fission power	400	MW
- Electric power	200	MW
- Overall power	700	MW

Additional heating power P_{aux} = 36 MW, including 30 MW neutral beams injection and 6 MW of ECR heating power at a frequency of 170 GHz.

DEMO plant mission is the following.

- Comprehensive testing of enabling systems and technologies of a steady-state FNS, including hybrid blankets, electric power generation and the radiochemical system.
- Tokamak discharges with durations of up to 5000 hours maintaining DT reaction with the fusion power higher than 40 MW should be implemented.
- Prototypes of FNS hybrid blankets realizing technologies of solid-state and molten-salt radionuclide breeding, and nuclear fuel cycle systems will be tested.
- Scientific and technical support of developing the pilot and industrial hybrid plants.

2. DEMO-FNS DESIGN

DEMO-FNS Design view is presented in Fig.1.

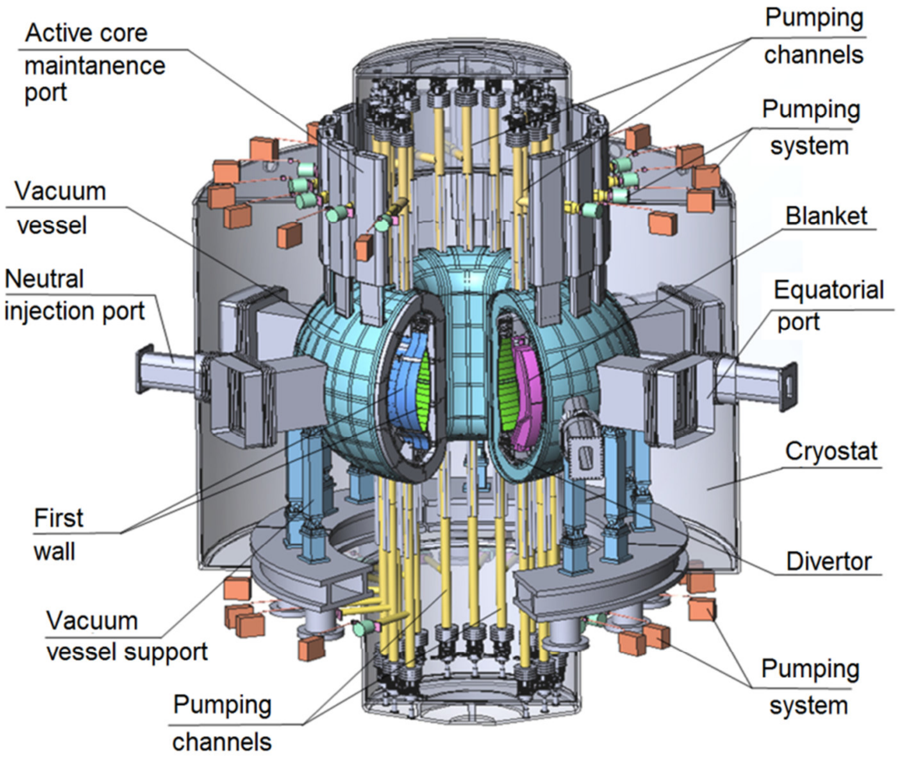


FIG. 1. DEMO-FNS cut-view (magnetic system not shown).

DEMO-FNS is a complex facility that includes a superconducting magnetic system, a vacuum vessel, a hybrid blanket located in it (consists of six modules), two (upper and lower) divertor units. The blanket module includes: blanket module body, transmutation active core, blanket breeder zone, coolant collectors.

3. MAGNETIC SYSTEM

Based on the suggested designing principles, the electromagnetic system (EMC) for the DEMO-TIN facility should ensure reliable operation of the system with a hybrid blanket and a corresponding hybrid nuclear fuel cycle. Superconducting electromagnetic system (EMS) of DEMO-FNS includes:

- Toroidal field coils (TFC) -18 units
- Central solenoid (CS) sectioned (6 units)
- Poloidal field coils (PFC) 4 pairs
- Correction coils (CC) 3 groups, 18 units
- Vertical control coils – 2 units
- HTS current leads

Materials used in toroidal and poloidal coils:

- Nb_3Sn, NbTi,
- SS, Cu-alloys
- insulator
- He-coolant

The configuration of the electromagnetic system and the vacuum vessel provides vertical loading of up to 18 active cores of the hybrid blanket and their remote maintenance with reloading into the special premises of the facility working building.

Analyses of the electromagnetic forces and the stress analyses of DEMO-FNS EMS were carried out. The most stressed units are the toroidal field coils (TFC). ITER like design for TFC was chosen after multi-option analysis. View of the toroidal coil and its finite elements mesh is shown in Fig. 2.

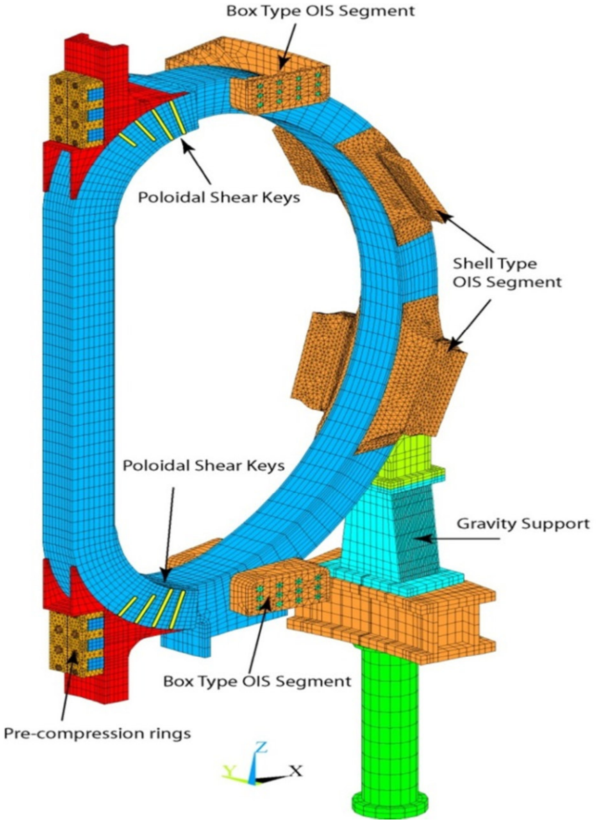


FIG. 2. View of the toroidal coil and its finite elements mesh.

Analysis of the stress-strain state of the coils showed that the proposed coils design meets the criteria of static strength (Fig.3).

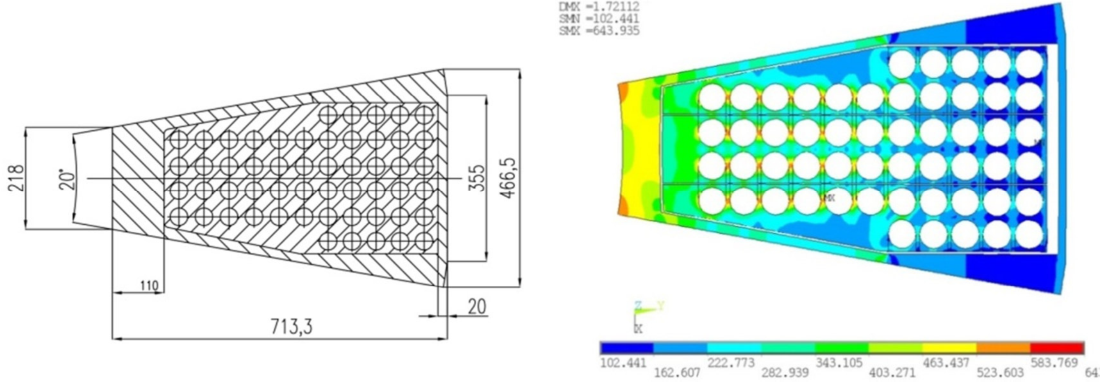


FIG. 3. Cross-section dimensions (a) and equivalent stresses (MPa) of the toroidal coil.

4. VACUUM VESSEL

The vacuum vessel (VV) is a welded two-layer toroidal shell (Figure 4) deposited inside the electromagnetic system. The free space between the vessel shells is filled with water and steel plates, which form the iron-water neutron protection of the electromagnetic system.

The vacuum vessel consists of the following main units (Fig. 1):
- the body of the vacuum vessel;
- equatorial ports, which provide access to the in-vessel volume for mounting and remote maintenance of in-vessel components, and plasma diagnostics;
- ports for injecting neutral beams into plasma;
- pipes for vacuum pumping;
- a supporting structure that takes up the weight of the VV and electromagnetic loads acting on the vessel;
- support system for fastening the divertor, blanket, turns of passive and active plasma stabilization, elements of the first wall and other components placed in the vessel;
- collectors of the water cooling system of the VV and in-vessel components.

The thickness of the VV at the inner side is 0.72 m, in order to reduce the volumetric heat generation rate in the materials of the superconductor of the toroidal field coils, in outer sections the thickness is 0.60 m.

At this stage of design the VV was considered, being adapted for a hybrid blanket with a steady-state breeding zone and a reloadable active core containing fuel assemblies with minor actinides (Fig 4.).

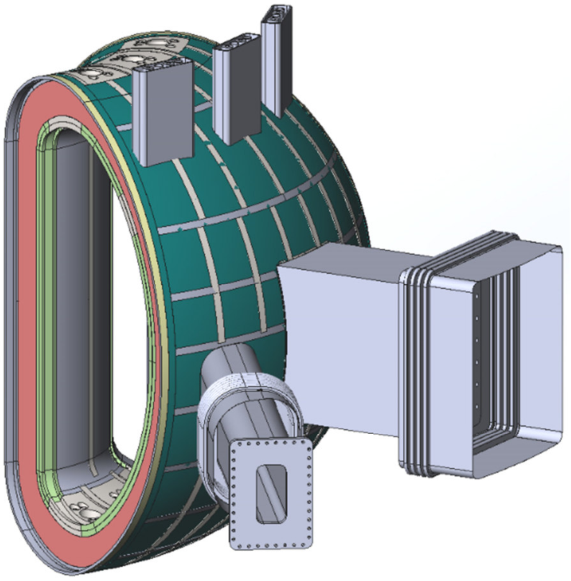


FIG. 4. General view of VV sector.

Vertical ports for reloading the blanket active core are located in the upper part of the vessel. Each sector has 3 rectangular branch pipes, in total there are 18 branch pipes in the FNS facility. With the existing arrangement of the blanket core reloading ports, pumping out tubes, cooling water outlet channels, the installation of mounting welded joints of the vacuum vessel sectors is possible only under the toroidal field coils.

Two supports are provided for the installation of the vacuum vessel on each sector. One of the supports is located under the equatorial port at the junction with the outer shell of the vacuum vessel, the other under the pipe for injecting neutral particles. At top and bottom, the supports are equipped with articulated joints that allow the vessel to move freely in the radial direction, compensating for the change in its dimensions at various operating temperatures. The supports in the lower part rest on supports, which are installed on a base common with the electromagnetic system. Dielectric inserts are provided between the supports, which electrically isolate the VV supports from the common base.

For convenience and minimization of the assembly time the vacuum vessel consists of 6 sectors, 60 angular degrees each.

5. BLANKET

Hybrid blanket of DEMO-FNS consists of two zones – active core (AC) and breeding zone (BZ):
- the AC includes 12 full-size units and 6 shortened ones;
- BZ, intended for reproduction of tritium, are placed on the outer part of the FNS VV for the entire operation life and are to be dismounted only in case of failure or emergency;
- reloading of the AC of the hybrid blanket of the FNS, the general view of which is shown in Figure 1, is carried out through the vertical service channels at the stopped facility;
- BZ modules mounting / dismantling is carried out through six equatorial (horizontal) service ports of VV.

The structure of AC, the general view of which is shown in Figure 5, includes: body, cover of the AC case, eight fuel assemblies containing fuel elements with a mixture of minor actinides (MA), two flexible mechanical supports. The AC of the hybrid blanket consists of 8 fuel assemblies with fuel elements containing a mixture of MA in a metallic form. Each fuel assembly consists of 56 fuel rods.

BZ modules are mounted on the external bypass of the VV. Mounting / dismantling of the BZ modules is carried out through the equatorial port of the in-vessel components of the FNS facility. Structurally, BZ is a canister structures that occupy all the available space located between the rear surface of the AC case and the surface of the VV. The breeding zone includes modules of various sizes. General view and volumes of BZ modules are shown in Figure 5. BZ modules are filled with lithium-containing ceramics - lithium orthosilicate (Li_4SiO_4) in the spherical form with a volumetric filling of at least 60% and a granule diameter of (1 - 1.5) mm. To accelerate the release of tritium and its subsequent removal of the BZ, a purge gas is pumped through the ceramics under a pressure of (0.15-0.2) MPa. Purge gas for tritium is helium with the addition of 1% hydrogen. Many coolants were taken into account during design development - liquid metal, water, water-steam mixture and supercritical CO_2 (SCO_2). Two last options seem to be preferable due to heat exchange hydrodynamics and neutron physics advantages.

6. MINOR ACTINIDES COMPOSITION

It is assumed that in the implementation of FNS with a hybrid blanket, the materials loaded by MA will have an exposure time of 10 to 50 years. The starting fuel composition corresponds to the MA composition obtained by 2050 after reprocessing spent nuclear fuel from thermal reactors within the framework of calculating the scenario of the development of nuclear power in the Russian Federation in a system of thermal reactors with a maximum achievable power of 28.5 GW. The composition of MA considered in the calculation is presented in Table 1.

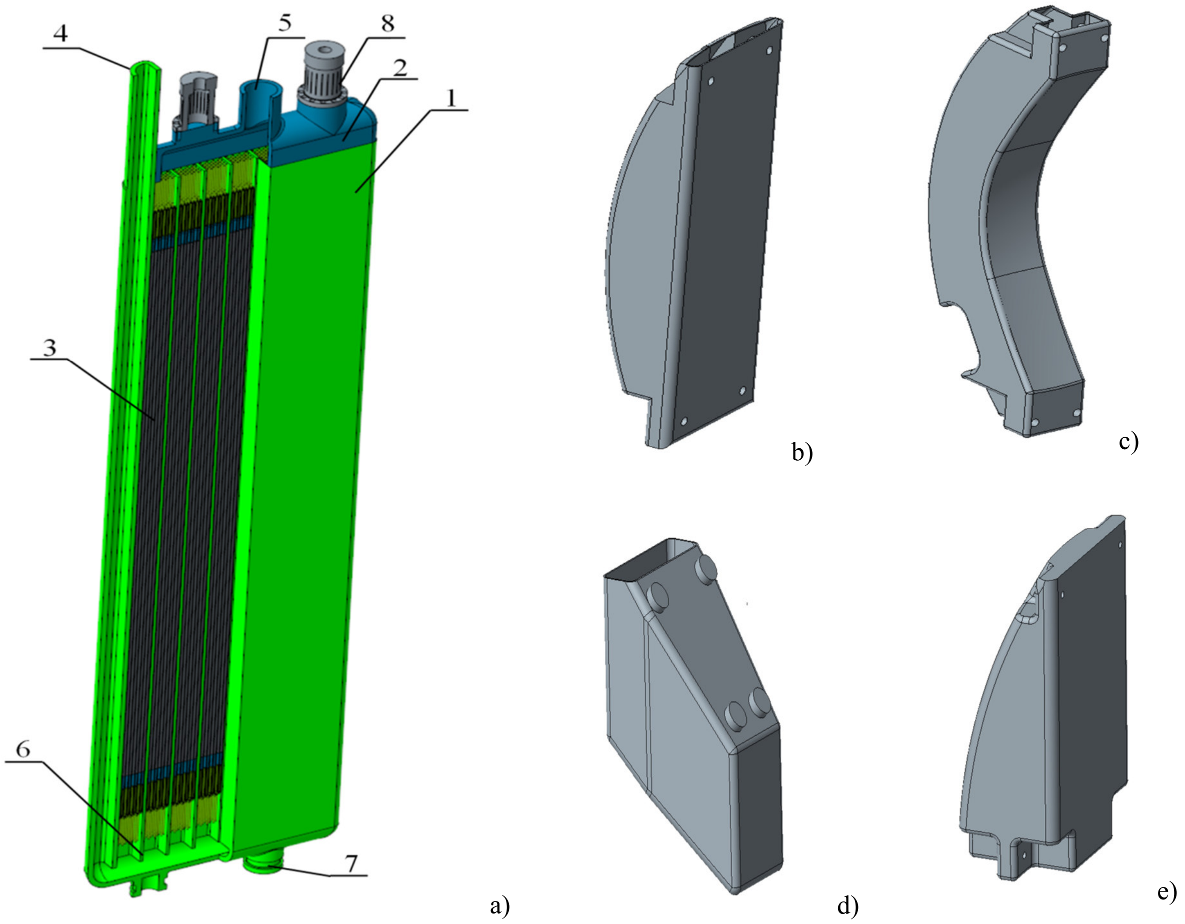
As a result of a joint thermo-hydraulic and neutron-physical calculation, the effective multiplication factor for the blanket with the given load reaches 0.94. In the process of convergence, an oscillatory process is observed. It should be noted that the limiting multiplication corresponding to $k_{eff} = 0.95$ is not achieved in the normal mode of blanket neutron-physical characteristics change insignificantly during the refueling cycle, and the k_{eff} value decreases less than 0.1%. Therefore, we can assume that k_{eff} during the campaign remains at the same level.

The transmutation efficiency of MA loaded into blanket during an overload cycle of 10 eff. years is 6% burnout of heavy atoms for the main AC and 8% of heavy atoms for small AC. In this case, the level of self-sufficiency in tritium breeding will be satisfactory.

7. INTEGRATION OF FFHS IN RUSSIAN NUCLEAR POWER ENGINEERING

The universal system model of nuclear power in Russia was chosen as an analysis tool. This tool was developed at JSC NIKIET under the leadership of E.V. Muraviev. The model is embedded in the USM-1 software product ("Universal System Model-1" [4]) and contains the history of nuclear power in Russia and forecasts for the future period from 1970 to 2130. This program allows working with a large number of information collected on all operating, as well as commissioned, power plants and provides the ability to extrapolate data up to 2130.

In this work assessment was carried out of the impact the fusion neutron sources operation on the amount of minor actinides (MA) in the nuclear power system (NP), taking into account the capabilities of the fuel cycle enterprises for SNF reprocessing and fuel fabrication.



1 – AC case; 2 - cover of the AC case; 3 – fuel assembly with fuel rods from MA; 4 - inlet coolant pipe; 5 - outlet coolant branch pipe; 6 – inter-channel partition; 7 - the counterpart of the collet fastening of the AC to the VV; 8 - flexible mechanical supports.

FIG. 5. General view of active core of DEMO-FNS hybrid blanket (a); general view of breeding modules (b, c, d, e).

TABLE 1. COMPOSITION OF MA MIXTURE, FROM SNF ACCUMULATED BY 2050

Nuclide	Mass fraction, %
^{237}Np	30.0
^{241}Am	65.0
^{242m}Am	0.06
^{243}Am	4.5
^{243}Cm	0.02
^{244}Cm	0.42

The following assumptions were taken into account.

- An optimistic and moderate scenario for the development of nuclear power was considered.
- Modeling takes into account export of nuclear power plants and reprocessing of the spent nuclear fuel (SNF) returned;
- SNF reprocessing - centralized and on-site.
- Modeling is carried out assuming the two-component nuclear energy in Russian Federation.
- The roadmap of the project at the moment provides for the construction of three facilities in the time interval from 2033 to 2055:

- DEMO-FNS (Year 2033) - loading: 100 t U, 20 t MA. Duty factor (DF) = 0.3; thermal power: 500 MW.
- Pilot FNS (Year 2045) - loading: 100 t U, 20 t MA. DF = 0.8; thermal power: 500 MW.
- Industrial FNS (Year 2055) - loading: 150 t U, 40 t MA. DF = 0.95; thermal power: 1365 MW.

The optimistic scenario for the development of nuclear power assumes the achievement of 115 GW of the installed capacity of nuclear power plants in Russia and 177 GW taking into account the installed capacity of exported NPPs by 2130. The moderate scenario of the development of nuclear power assumes the achievement of 67 GW of the installed capacity of nuclear power plants in Russia and 123 GW taking into account the installed capacity of exported NPPs by 2130. The results of the analyses are shown in Figs 6-7.

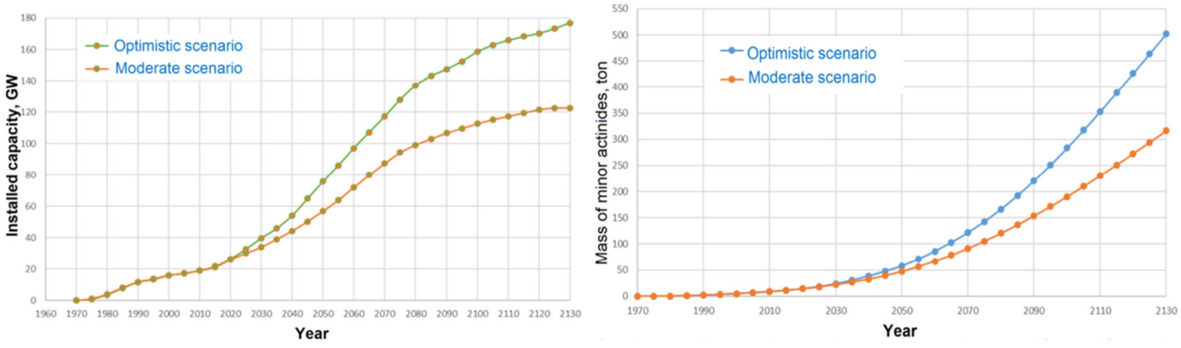


Fig. 6. Installed power of nuclear power plants in Russia and export nuclear power(a); amount of accumulated MA in the nuclear energy system (b).

Optimistic scenario of nuclear power development assumes SNF reprocessing enterprises will produce 472 tons of MA by 2130, of which 374 tons of MA will remain, taking into account the operation of the FNSs, provided that blanket is fully loaded. Moderate scenario of nuclear power development, SNF reprocessing enterprises will produce 170 tons of MA by 2130, of which 72 tons of MA will remain, taking into account the operation of the FNSs, provided that blanket is fully loaded.

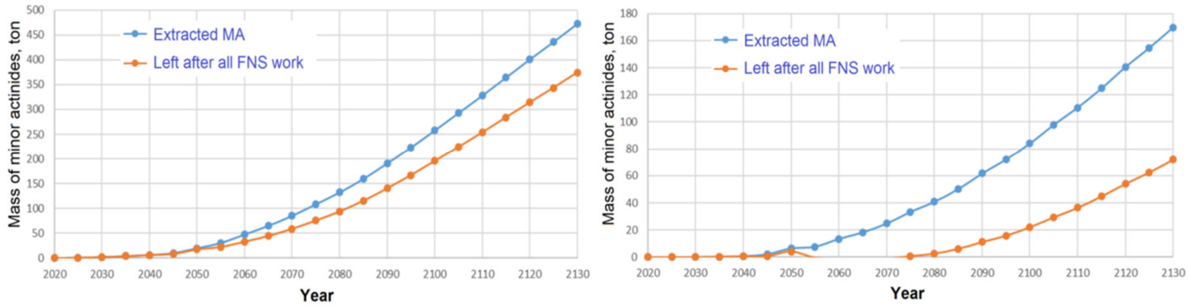


Fig. 7. Mass of allocated MA in the nuclear energy system of Russia (+ export). Optimistic scenario (a); Moderate scenario (b).

From the results obtained, it can be assumed that 3 - 4 hybrid systems are able to ensure the balance of the produced and transmuted MA in the power system, provided that the necessary capacities for SNF reprocessing and fuel fabrication are provided.

Evolution of specific activity for MA, fission products and decay products during and after single irradiation in DEMO-FNS (per 1 ton of initial fuel) was analyzed (Fig. 8).

The MA activity after irradiation remains slightly higher than that initial. MA total amount decreases. 906 kgs from 26 tons of very active materials are transmuted into decay the activity of which decreases much faster. The rest of MA ceases to belong to the waste class and is included in the nuclear fuel cycle, where it is gradually converted into fission products. At the beginning of 2021, the Russian government adopted a program for the development of fusion-fission hybrid systems. Scientific management was entrusted to NRC "Kurchatov Institute".

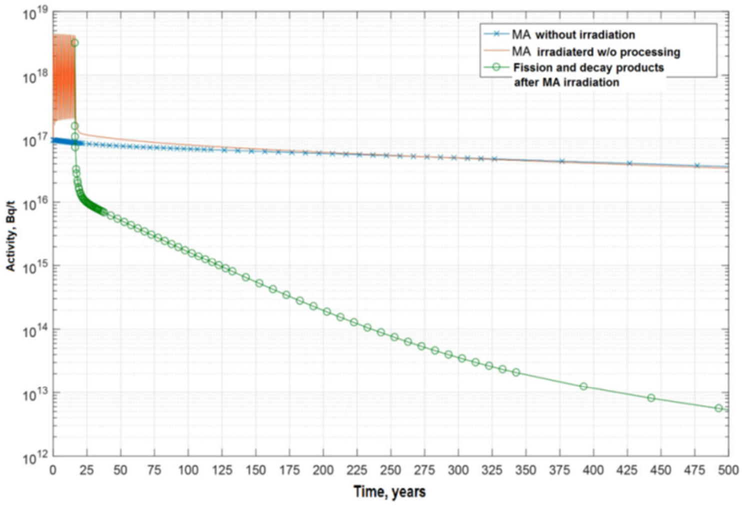


FIG. 8. Evolution of specific activity for MA, fission products and decay products during and after single irradiation in DEMO-FNS.

8. CONCLUSIONS

Enabling systems of DEMO-FNS were upgraded including Vacuum vessel, Radiation shield, Divertor, Blanket, Fueling cycle. Design activity was supported by R&D in Neutronics, Optimization of the device layout, Subsystems including EMS, VV, divertor, blanket and T-fuel cycle3 to 4 Industrial FNS systems are capable of ensuring the equilibrium of the produced and transmuted MA in the RF nuclear power system, provided that the necessary capacities for SNF reprocessing and fuel fabrication are implemented.

9. REFERENCES

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10. FURTHER INFORMATION

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