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Fusion Reactor with Internal Neutron-Helium-3 Plasma Heating

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Review Article

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ABSTRACT

The creation of thermonuclear reactors with a catalytically supported approach to the implementation of thermonuclear energy with high power density and dynamic stability is proposed. In the reactor, internal neutron heating of the plasma takes place on D-^{3}He fuel composition with a catalytically stabilized composition, the fuel is heated by interacting with thermal neutrons and the resulting plasma is heated with a regime of radial localization and acceleration along the magnetic field. The formation of a reactor fuel cycle closed for tritium, helium-3 and neutrons is underway. They burn out in the process and are built up again. The high efficiency is due to the fact that the cross section and reaction rate of neutrons with (σ_{n3He} and $\langle \sigma v \rangle_{n3He}$) are higher than the values of other thermonuclear reactions over the entire temperature range. The use of Retarding Focusing Structure (RFS) a thermalization device and the formation of a directed neutron flux, makes it possible to increase the density in the flow of thermal neutrons returned to the plasma by means of the RFS by more than a $\sqrt{10^7/0.025} \approx 2.10^4$ factor. (Here the energy of the emerging fast ions is 107 eV, the energy of thermal neutrons is 0.025 eV.) Thermal neutrons interact in the plasma with ^{3}He, in this case fast ions T are born interacting with D-^{3}He of the fuel composition and the energy release in the reactor increases, the neutrons return and then the hot plasma is removed to form a thrust pulse of a jet engine or for conversion into electrical energy. Modeling allowed us to conclude that a fusion reactor with an internal catalytic cycle can be quite compact.

Keywords: Thermonuclear reactor; Catalytically closed internal fuel cycle; Neutron flux control; Thermal neutron separation effect; Moderating-focusing structure; Thermonuclear jet engine

INTRODUCTION

The development and improvement of new technologies for their subsequent use in the thermonuclear reactor of the International Thermonuclear Experimental Reactor (ITER) project is one of the most relevant areas of nuclear energy at the present stage. Heating and formation of thermonuclear plasma requires the use of external energy sources. Two mechanisms for supplying energy to heat the plasma are proposed in the form of injected external beams of fast particles with adiabatic compression of the "cold" plasma, or by an external magnetic field by initiating powerful ring or linear currents in the "cold" plasma [1-4]. In any case, when using external methods of plasma formation and heating, it is necessary to return the heating energy and fulfill the Lawson criterion, which characterizes the critical parameters of the conditions for the return of expended energy. An alternative solution may be a thermonuclear fusion reactor, in which the heating and formation of plasma to the temperatures required for thermonuclear reactions occurs due to internal exothermic nuclear reactions. Similar heating was previously used in a thermonuclear bomb the only realized device in which thermonuclear fusion reactions occur. A thermonuclear reactor has been proposed that uses internal plasma heating by thermal neutrons through the interaction of its fuel composition, including ^3He and D, operating in a catalytically closed mode [5,6].

Basic provisions of the fusion reactor

Thermonuclear reactors currently being created are characterized by a low energy density in the plasma. For example, in thermonuclear plasma, tokamak ITER, the energy release power in the plasma is 0.6 watt/cm^3 at the peak of the pulse. This fact is the reason for the creation of bulky and expensive tokamaks, in particular, the ITER project with characteristic dimensions (height and diameter of the reactor) of up to 40 m and with requirements for compliance with the Lawson criterion. In the thermonuclear reactor we propose, the plasma is localized in a longitudinal magnetic trap by end magnetic plugs. A cold fuel mixture, including D-^3He, is introduced and heated by interaction with thermal neutrons at the axis or at the end of the trap, forming a region of hot thermonuclear plasma moving to the periphery of the trap, where the released energy is removed. Fast neutrons are thermalized and returned to the reactor. The reactor operates in continuous mode. The plasma is magnetized so that its radial diffusion is limited.

Let us consider the processes occurring in the reactor plasma.

The interaction of D+D nuclei in plasma occurs through two equivalent channels [5,6]

(50%) $D + D \rightarrow T\ (1.01\ MeV) + p\ (3.02\ MeV)\ Q = 4.03\ MeV$ (1)

(50%) $D + D \rightarrow {}^3He(0.82\ MeV) + n(2.45\ MeV)\ Q = 3.27\ MeV.$ (2)

^3He has a large σT=5400 barn, cross section for interaction with thermal neutrons

$^3He + n \rightarrow T(0.19\ MeV) + p(0.57\ MeV)\ Q = 0.76\ MeV$ (3)

In this case, fast tritium T (0.19 MeV) is produced, interacting with D

$D + T \rightarrow {}^4He\ (3.50\ MeV) + n\ (14.1\ MeV).$ (4)

A feature of reaction (4) is its high energy release: Q=17.6 MeV.

Where Q is the energy release of the reaction.

The interaction of generated fast tritium with 3He also occurs in the following reactions

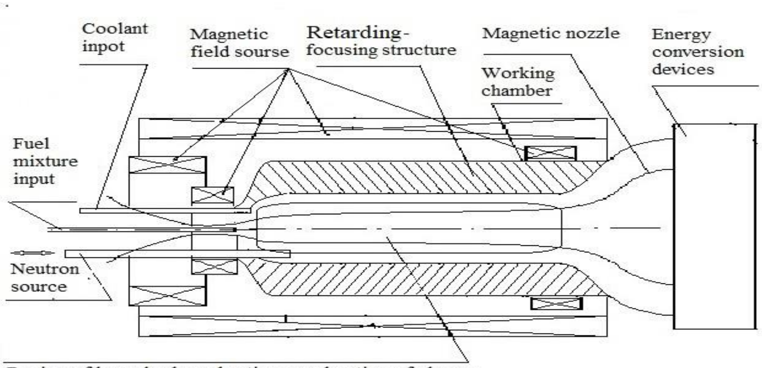
(51%) $^3He + T \rightarrow {}^4He + p + n\ Q = 12.1\ MeV,$ (5)

(43%) $^3He + T \rightarrow {}^4He(4.8\ MeV) + D(9.5\ MeV)\ Q = 14.3\ MeV,$ (6)

and (6%) $^3He + T \rightarrow {}^5He(2.4\ MeV) + p(11.9\ MeV)\ Q = 14.3\ MeV.$ (7)

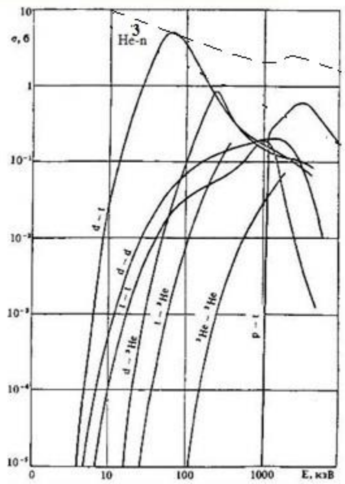
The reaction also occurs as $D + {}^3He \rightarrow {}^4He(3.6\ MeV) + p(14.7\ MeV) Q = 18.3\ MeV$. (8)

Figure 1. Basic fusion reactor-internal catalytic cycle engine.



In the reactor, a device for thermalization and formation of a directed neutron flux a Regulatory Focusing Structure (RFS), covers the localization region of hot plasma and is located inside the system for forming the magnetic field of an open trap. Thermalization of fast neutrons makes it possible to increase the density in the flow of returned thermal neutrons to heat the input cold fuel mixture of ^3He and D, T. The speed (temperature) of thermal neutrons is much lower than the speed (temperature of the plasma and the energy and energy of fast ions born in the plasma). After heating in the n^3He reaction, the path length in the plasma before interaction is determined by the path length of ^3He ions magnetized in a magnetic field, which wind up kilometers before interacting with an almost stationary, relative to them and increased more than $\sqrt{10^7/0.025} \approx 2.10^4$ times, up to 10^{14} cm^{-3}, return flow RFS of neutrons. The energy of the generated fast ions is 10^7 eV, the energy of thermal neutrons is 0.025 eV. The flux of returned neutrons at the surface of the plasma column increases in the process of integration of the neutron flux of the plasma volume to its boundary as the ratio of the plasma volume to its surface (V/S) and then there is an increase in the neutron density in the neutron flux during the reverse movement directed towards the reactor axis after the Zero Flux Surface (ZFS) of thermal neutrons due to the concentration of the thermal neutron flux directed by the RFS as 1/r, where r is the distance to the reactor axis. Let us give graphs of the cross sections of the main thermonuclear reactions.

Figure 2. Cross sections for main reactions [4], n^3He cross section added [7].



The cross section for the interaction of cold ^3He with thermal neutrons is 5400 barn. Despite the fact that in hot plasma it drops to several barns, it is extremely important that the reaction cross section σ_{n3He} and the reaction rate $\langle \sigma v \rangle_{n3He}$ of neutrons with ^3He are much higher than all other thermonuclear reactions in the entire temperature range and dominate over other processes. The modeling proceeded in several steps. Previously, in [6-8], the operating mode was shown for catalytically closed stationary plasma burnup, when in a hot 15 keV (kilo-electron volts) plasma the production and burnup of D, T and ^3He are equal. At the same time, in a composition of 57% D and 43% ^3He, 42% of neutrons are produced in Deuterium-Deuterium (DD) reactions and 58% of neutrons are produced in Deuterium-Tritium (DT) reactions. In this case, the fixed, generated volumetric neutron flux obtained for the catalytically ensured operating mode is.

$$B_{nplasm} = \frac{1}{2}\langle \sigma v \rangle_{DD} \cdot n_D^{\,2} + \langle \sigma v \rangle_{DT} \cdot n_D \cdot n_T + 0.51.\langle \sigma v \rangle_{HeT} \cdot n_{He} \cdot n_T + 2\langle \sigma v \rangle_{TT} \cdot n_T^{\,2} \tag{9}$$

Where, B_{nplasm}=4.6·10^{13}cm^{-3}c^{-1} is the flux of neutrons produced in thermonuclear plasma and 44% of the energy is carried away by neutrons. Then the dynamics of plasma heating in an open magnetic trap were considered when a cold fuel mixture was introduced and its interaction with thermal neutrons in the trap. The composition of the fuel mixture is taken as a basis, including 57% D and 43% ^3He and 0.1%-1% T. The model assumed that the heating process of the mixture is isobaric. Plasma temperature and density are inversely proportional. The starting pressure in the inlet composition is 0.15 atm, density 5·10^{18} cm-3. Mass flow rate of the input mixture M_{in}=3.8 × 10^{-3} g/s (for helium-3 M_{inHe}=2 × 10^{-3} g/s).

Dimensions of the burnout area in a longitudinal magnetic trap: Radius R=0.2 m, length L=2 m.

Reactions proceed with a large release of energy, neutrons are born again and the process closes with the flow of neutrons. For this case, the dynamics of energy release was considered when introducing the fuel mixture into an open trap from ^3He-n reactions, with a fixed B_{nplasm}.

$$W_F(r) = W_{plasm} + k\left(E_T = +0.002.21\%.E_{DT}\right).\frac{K_{V/S}}{V_n}.\frac{R_{plasm}}{r}.\sqrt{\frac{E_n}{T_O}}.\left(\langle \sigma v \rangle_{n3He}.B_{nplasm}.n_{3He}\right) \tag{10}$$

Here r is the distance from the axis; W_{plasm} – energy release from ions in hot 15 keV plasma; k–Boltzmann constant; E_T = 0.19 MeV – fast T energy; E_{DT} = 3.50 MeV – energy of fast ^4He (accepted-0.002 fraction of fast T that immediately reacted with D); R_{plasm} – outer radius of plasma; v_n= 2.2*10^3 m/s - speed of thermal neutrons; $K_{V/S} \approx V/S$ – coefficient of volumetric flux integration – the ratio of the plasma volume to the area of its lateral surface; $E_n \approx$ 10 MeV – average energy of fast neutrons; T_0 = 0.025 eV – energy of thermal neutrons. It is important that $\langle \sigma v \rangle_{n3He} \approx$ is constant and the density of helium-3 decreases with increasing temperature.

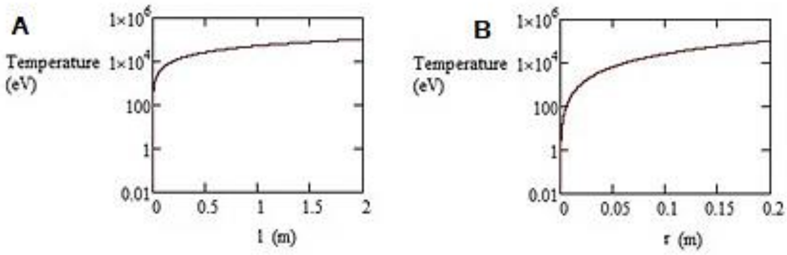
Under these conditions, the course of plasma temperature growth was integrated.

$$T_{plasm} = \int_o^v \frac{W_F(r)}{\left[\frac{C_p}{d^3He.\mu He + dD.\mu D + dT.\mu T}.\frac{M_{in}}{V}\right]}.\frac{dV}{V} \tag{11}$$

Here d-^{3}He=0.427, dD=0.563, dT=0.01, Cp=20.724 J/K, V= π R^2L

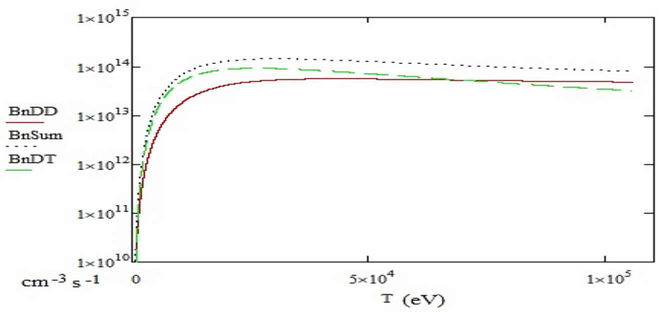
Options for axial plasma motion along the trap $\frac{dV}{V} \to \frac{dl}{L}$ and radial motion $\frac{dV}{V} \to \frac{2\pi r dr}{\pi R^2}$ (input, heating, combustion and output of hot plasma from the periphery in the plasma trap) were considered. The heating and combustion process is continuous.

Figure 3. Dynamics of temperature growth (in eV) from ^{3}He-n reactions when introducing the fuel mixture along the axis and during radial heating of the plasma depending on the distance from the axis. **Note:** A) Dynamic temperature growth above 100 in (eV); B) Dynamic temperature growth below 100 in (eV).



In the variant of introducing the fuel mixture into the paraxial region of the trap with magnetic plugs at the ends, the maximum energy release occurs in the paraxial region where the input fuel mixture with a density of about ≈ $5{\cdot}10^{18}$ cm^{-3} (0.15 atm) is heated to keV temperatures already in the first centimeter, reaches the operating plasma temperature at a length of 2 cm and combustion occurs with the release of thermonuclear energy in the charged and neutron ranges. The trap passage time during axial heating in isobaric mode is 3.2 s. When the mixture is introduced axially, the preservation of the isobaric heating process in the trap is determined by the ratio of the magnetic field values in the entrance and exit plugs of the trap and the equality of the mass flows at its entrance and at the exit of the hot plasma from the trap. In the variant of introducing the fuel mixture in the paraxial region of the trap and the radial movement of the plasma with end magnetic plugs at the ends, the maximum energy release occurs in the paraxial region, where the input fuel mixture is heated to keV temperatures already in the first centimeter and reaches the operating plasma temperature at a diameter of 2 cm. During radial heating, the magnitude of the axial magnetic field is reduced to ensure isobaric radial drift of the plasma and the magnitude of the end plug field is maximum. The trap passage time during radial heating in isobaric mode is 6.4 s. At the second step, for the reactions: D+D ⟶ p+T, D+D ⟶ n+^{3}He, D+T ⟶ n+^{4}He, D+^{3}He ⟶ p+^{4}He, smooth approximations of the dependence of reaction rates on energy were obtained from [9-11]. Based on the knowledge of the dependence of these cross sections on energy, an estimate was made of the volumetric flux of fast tritium and the flux of neutrons produced in these reactions during plasma heating (Figure 4).

Figure 4. Dynamics of growth of the volumetric neutron flux ($cm^{-3}s^{-1}$) from DD reactions and from reactions D with T at 1% T, when introducing a fuel mixture, depending on the plasma temperature.



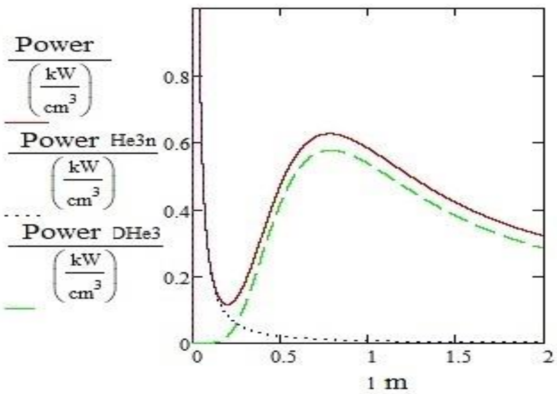
In this case, B_{nDD} is the volumetric flux of neutrons in ($cm^{-3}s^{-1}$) generated from DD reactions in plasma and B_{nSum} is the neutron flux taking into account the fluxes B_{nDT} and B_{nTT} from DT and Tritium-Tritium reactions (TT). It is important that in order for the process of neutron production and burnout to be mutually assured, it is necessary to introduce from 0.1% to 1% tritium into the fuel composition at the inlet. At 1% T, the flux B_{nSum}=1.0 × 10^{14} cm^{-3} s^{-1}, which is greater than the initial calculated catalytically provided value B_{nplasm}= 4.6 × 10^{13} cm^{-3} s^{-1} and the neutron flux resumes in the cycle. Since the technological albedo of the RFS is greater than unity, it is possible to operate the reactor without input of T, which increases the safety of the reactor. Energy release taking into account the interaction of ^{3}He with thermal neutrons, D and T. Taking into account that the path length of thermal neutrons before interaction is still greater than the transverse dimensions of the reactor and also taking into account that the density and concentration in the composition decrease with increasing temperature in the heated composition and in the plasma, then the energy release in the plasma taking into account the interaction of ^{3}He with thermal n, c D, T, this expression, more precisely, will be.

$$W_F(r) = k.\frac{1}{4}E_{He3n}\cdot\left(k_{v/s}\cdot\frac{n_{3Hezag}}{n_{3He}}\cdot\sqrt{\frac{T_o}{T_{Plasm}(r)}}\cdot\frac{2.R^2_{plasm}}{r}\cdot\left[\frac{E_n}{T_0}\right]^{\frac{3}{2}}\cdot\left(\sigma^2_{n3H}\cdot\left(B_{nDD}+B_{nDT}+B_{nTT}\right).n^2_{3He}\right)\right) \quad (12)$$

Where σ_{n3He}=5.4 barn at an energy of 15 keV, $^3He_{gaz}$ is the concentration of ^{3}He in the input mixture.

Let us consider the energy release in the plasma taking into account the interaction of ^{3}He, with thermal neutrons, with D and T. We obtain the following power release in the plasma (Figure 5).

Figure 5. Dynamics of growth of energy release (kW cm^{-3}) from reactions with ^{3}Hen during heating and from DD, DT, ^{3}HeT and TT reactions when introducing the fuel mixture along the axis.



It is taken into account that the path length of thermal neutrons before interaction is greater than the transverse dimensions of the reactor and that the density and concentration in the composition decrease with increasing temperature in the heated composition and in the plasma. It can be seen that due to the negative effects of plasma overheating, for maximum neutron yield, with the accepted initial data, it is advisable to reduce the length of the trap to 1 m and the radius of the plasma in the trap to 0.1 m. When reducing the mass flow rate of the input mixture down to M_{in}=1.10^{-4} g/s the dimensions of the reactor can be further reduced and made more compact. In a thermonuclear reactor, heating occurs in ^{3}He-n reactions, burnup occurs mainly in D-^{3}He reactions and energy is removed during the expansion and acceleration of the introduced fuel mixture. The reactor operates in the mode of a neutron-helium plasma torch with a magnetic field. The reactor is not a plasma confinement device. Its purpose is layer by layer localization, plasma heating, plasma acceleration and energy removal. The plasma temperature during operation changes significantly and the operating mode of the reactor changes from the helium3-neutron mode to the stage of tritium dominance in the catalytically closed operating mode.

Let us consider the dynamics of changes in plasma temperature along the reactor axis during operation of a thermonuclear reactor. The mixture heats up in reactions with neutrons and moves towards the outlet end of the reactor. Heating occurs layer by layer with the thickness of the layers determined by the larmor radii of hot ions ≈ 1 m and electrons. As it moves, it warms up, accelerates and increases the specific volume of the mixture in the ratio (up to 15000 eV/0.025 eV ≈ $6{\cdot}10^5$ times). Thermal conductivity of plasma is $1.38{\cdot}10^6$ W/m·K, Thermal conductivity of plasma across the magnetic field is $4.6{\cdot}10^{-8}$ W/m·K with a longitudinal magnetic field of 10 T. Partial energy removal occurs through the thermal conductivity of the external outer wall of the magnetized plasma of the reactor. The plasma is washed from the outside with a coolant that does not contain helium-3, for example, D or hydrogen, so that the energy release from ^{3}He-n reactions in the plasma is torn away from the walls, removing part of the energy and fixing this outer boundary from hot plasma hitting the walls.

In order for a certain system to be stable and for a stationary process to exist in it, it is necessary that the energy release be equal to the energy loss and at the same time not exceed a certain critical value for the system. Therefore, a stationary thermonuclear reactor requires a system for continuously removing the released energy. When the reactor operates in continuous mode and the plasma is removed from the trap after the external magnetic plug, the temperature of the emerging plasma is incommensurate with the maximum temperature of the order of 1000˚C-3000˚C, which is allowed by modern materials. And the plasma at the output must be diluted with an external coolant to convert and usefully use its energy by more than 4.10^5 times. When using the process as a thermonuclear rocket engine, there is a magnetic nozzle at the output of the reactor, in which, in an expanding magnetic field, the plasma energy is converted into the kinetic energy of a flow whose speed reaches 10^6 m/s.

Note, when the reactor is operating in the radial drift mode, the reactor can consist of two base reactors installed counter to each other with a central radial output of hot plasma to a ring external energy converter including a radial Magneto Hydro Dynamic (MHD) generator.

Experimental basis for neutron control

In 1991, to improve the efficiency of controlling thermal neutron fluxes, the RFS was developed a moderating-focusing structure based on anisotropic smoothly profiled structures of an elliptical profile [6,8]. The creation of a device with the ability to select neutrons according to direction in space is based on the use of the effect of neutron reflection from the surface of materials [12-16].

In the RFS there are two processes in parallel: The process of neutron scattering on the nuclei of matter, including the deceleration of the initial fast neutrons entering it and the subsequent rescattering of thermal neutrons in it in the form of a diffuse field with its maxwellian energy spectrum.

The process of selection of thermal neutrons from the diffuse field in the anisotropic structure of the RFS formed from thin profiled plates from the moderator with channels between them oriented in the selected direction of the focal areas and in the sharply anisotropic structure of the RFS in the form of a package of selecting plates, each neutron after scattering has a probability of falling into the angular region of neutron capture by any of the selecting plates inside the package of the structure. The result of the movement of neutrons near the surface of the plates, the radius of curvature R of which smoothly increases, is a series of successive reflections: A wall neutron, having reflected from the surface of the plate for the first time, experiences a series of subsequent reflections. The experiments were carried out in the Gidropress Experimental Channel 4 (GEK-4) at the Innovative Research Reactor-

Tank Type (IRT-T) reactor of the National Research Tomsk Polytechnic University [15]. At least twofold increase in the average integral flux of thermal neutrons from a sector (1/45) ZFS on a control silicon wafer is shown. On the control silicon wafer, the background heat flux of the reactor was recorded, plus the neutron flux that entered the RFS sector was selected and recorded on the wafer. Thus, the flow capture by the structure is registered and corresponds to the calculation of the flow divergence along the angle at the exit from the RFS plates.

Starting dynamics of work processes

There are two possible options for starting the reactor: Neutron and plasma start. During a neutron launch, the internal volume of the longitudinal trap chamber of the reactor is filled with a cold gas working mixture, for example, of 68% deuterium and 31% helium-3 under a pressure above 0.02 atm. In this case, the path length of a thermal neutron before absorption by helium-3 will be comparable to the transverse dimensions of the longitudinal trap of the reactor (d ≈ 1 m). The thermonuclear reactor chamber is magnetized, in our case up to 10 T. To start from an external pulsed source, fast neutrons are directed into the RFS through a window from the outside or enriched fissile material is introduced into it. Neutrons are thermalized, selected and directed along the longitudinal selection plates of the RFS to the reactor axis. The starting pulse of the external reactor as a source of neutrons, as well as the injection of fissile material, can last no more than 10^{-3}-10^{-1} seconds. During a plasma launch, the thermonuclear reactor chamber is heated to plasma temperatures, intermittently increasing the field in our design case to 10 T, with additional beam heating.

Fuel base

A powerful production facility for producing helium from natural gas has been created in the Russian Far East. At the same time, Public Joint Stock Company (PJSC) Cryogenmash, a subsidiary of rosatom, has developed and patented a new technology for extracting helium-3 and created a special installation for extracting helium-3 from liquid helium with an efficiency of 99.9%. Therefore, the question of a source of helium-3 for operating a reactor based on helium-3-deuterium plasma is removed.

CONCLUSION

Experimental confirmation of the performance of the RFS design, an anisotropic thermal neutron concentrator made in the form of a package of plates made of profiled graphite and aluminum, was obtained in experiments at the reactor. It allows you to increase the efficiency of the return of thermal neutrons to the thermonuclear reaction zone. The ability to thermalize fast neutrons using RFS and control the behavior of thermal neutrons by directing them to selected focal areas of the structure makes it possible to create a new type of thermonuclear reactors. The high efficiency of the reactor is due, first of all, to the fact that the energy release and cross section for the interaction of neutrons with ^{3}He are higher than all other thermonuclear reactions in the entire energy range. The use of a Slow Focusing Structure (RFS) allows one to increase the density in the flow of returned thermal neutrons by more than $\sqrt{10^7/0.025} \approx 2.10^4$ a factor. The interaction length in the reactor is determined by the path length of energetic ^{3}He ions magnetized in a magnetic field. The mode of a neutron helium-deuterium burner is implemented. The reactor operates with tritium, helium-3 and neutrons returned to the cycle. A fusion reactor with an internal catalytic cycle is feasible, can be quite compact and can be used for propulsion and power generation.

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