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WHAT CAN AND CANNOT BE EXPECTED FROM TOKAMAK FUSION

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*This article is a response to the analysis of nuclear fusion by V. V. Orlov and L. I. Ponomarev in their article "Nuclear problems of thermonuclear power generation" [Atomnaya Energiya, **124**, No. 2, 105–110 (2018); Atomic Energy, **124**, No. 2, 129–138 (2018)], pointing to the decades-long lack-of-progress in thermonuclear energy research. The authors of the article attribute the lack-of-progress to fundamental problems in the nuclear aspects of thermonuclear fusion. Here, the reason for the current stagnation – essentially, the ~~degeneration~~ [degradation] of thermonuclear fusion that commenced in the 1950s–1970s with rapid development – is presented. The scientific investigations have been and remain within the scope of the Tamm–Sakharov concept of toroidal plasma confinement, which provided the first impetus to progress but soon showed its insufficiency. ~~An~~ [Here, an] additional element is considered – the suppression of plasma cooling by using ~~moving~~ [flowing (creeping)] liquid lithium to pump out plasma. For tokamaks this opens up new prospects for obtaining burning plasma suitable for use in hybrid (fission-fusion) reactors.*

This article is a response to the article "Nuclear problems of thermonuclear power generation" by V. V. Orlov and L. Ponomarev [*Atomnaya Energiya*, **124**, No. 2, 105–110 (2018); *Atomic Energy*, **124**, No. 2, 129–138 (2018)] pointing to the decades-long lack of progress in research on thermonuclear power generation. This situation sharply contrasts with the impact of general physics and technology on society during the same period of time. The authors attribute the lack of success to fundamental problems in the nuclear aspects of thermonuclear fusion. Actually, fusion research is still far from these expectant future challenges and it is not clear whether or not it will ever reach the level of maturity needed to face nuclear problems.

This article describes the reason for the current stagnation – in essence, the ~~degeneration~~ [degradation] of thermonuclear fusion commencing in the 1950s–1970s with rapid development. At the same time, scientific research was and remains within the framework of Tamm–Sakharov concept of toroidal plasma confinement, which gave the first impetus to progress but soon revealed its insufficiency. This was proved in the mid-1990s by the inability of the two largest tokamaks TFTR (USA) and JET (Great Britain) to achieve in DT [deuterium-tritium] experiments a fusion energy gain factor equal to 1. The problem with the approach itself was not realized, and research was continued without resolving it. Nonetheless, some researchers drew the correct conclusion from these and decisive experiments on the T-11M tokamak (Russia) and realized the necessity and possibility of suppressing the cooling of the plasma boundary by recycling [of] the plasma on the walls. The suppression of plasma cooling is a new element that radically changes the plasma confinement regimes of the Tamm–Sakharov concept. In the new approach, the two most difficult parts of tokamak physics that impede progress – the loss of energy from plasma due to heat conduction and the ~~complex~~ [complicated] interaction of the plasma with the first wall – are losing their relevance for the development of thermonuclear fusion. Based on much cleaner general physics [rather] than plasma physics, the new regimes correspond to the implementation of the original idea of magnetic fusion – isolating high-temperature plasma from material surfaces. This new approach will advance tokamak fusion to the level needed for solving real nuclear problems.

Around 1978 V. V. Orlov made a presentation on the place of thermonuclear fusion in power ~~engineering~~ [generation], wherein he noted that the destruction of structural materials by 14 MeV neutrons is one of the fundamental problems of the fusion

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approach to energy production so that nuclear fusion in power engineering can only be thought of as a component of nuclear energy. In [1] this was explained in detail with emphasis on the production of tritium as a fuel for a thermonuclear reactor. In the present article it is shown that the destruction of materials is an obstacle that makes a purely thermonuclear power reactor impossible.

Now about the current situation in fusion and its readiness for energetics. Unfortunately, admittedly, it must be recognized that there is no rigid link between the energy produced from fusion and the lifetime of materials. At the same time, it eliminates any hope for a clean fusion reactor.

A large but limited amount of energy can potentially be extracted from 1 kg of tritium, here termed the energy constant C^{FE} from fusion. It is calculated, in joules (J), as

$$C_{\mathrm{J}}^{FE} = 17.59\cdot10^{6}\cdot1.602\cdot10^{-19}\cdot(6.022\cdot10^{23}\cdot10^{3}/3) = 566\cdot10^{12},$$

where $17.59\cdot10^6$ is the energy released in one DT-fusion reaction (deuterium-tritium), MeV; $1.602\cdot10^{-19}$ is a coefficient for converting electron-volts of tritium into joules, J/eV; $6.022\cdot10^{23}\cdot10^3/3$ is Avogadro's number multiplied by 1000 and divided by the mass of tritium 3 (in terms of protons), i.e., the number of tritium atoms in 1 kg. In [1] the equivalent constant C^{FE} is given as $3.5\cdot10^{24}$ MeV/g = $566\cdot10^{12}$ J/kg.

The energy fraction C_n^{FE} delivered by the neutrons from 1 kg of tritium (the energy of the α-particles is excluded) is equal to

$$C_{n,\mathrm{J}}^{FE} = 14.07C_{\mathrm{J}}^{FE}/17.59 = 453\cdot10^{12}.$$

Aside from the numerical value, C^{FE} has another important specific value for fusion. Neutrons from a DT-reaction not only carry useful energy, they also damage the first wall (FW), which is the first 10–15 cm of materials in the path of 14.1 MeV neutrons from the plasma. Above a certain neutron fluence, i.e., time-integrated flow, the structural material of the first wall (solid part) becomes brittle, swells, and must be replaced. The conditional critical value C^{FW} used here for such a maximum fluence is C^{FW} = 15 MW·yr/m^2, which corresponds to about 150–200 dpa.

Actually, the number 15 is optimistic for estimating the service life of the first-wall structural materials. In reality, it is about 3 times shorter. But it is convenient to use the number 15 because of the accidental relation $C^{\mathrm{FW}} \sim C_n^{FE}$. In joules,

$$C_{\mathrm{J}}^{\mathrm{FW}} = 15\cdot10^{6}\cdot365\cdot24\cdot3600 = 473\cdot10^{12} \sim C_{n,\mathrm{J}}^{FE}.$$

The meaning of this equality is simple: the lifetime of the first-wall material corresponds to the consumption of 1 kg of tritium on the most vulnerable 1 m^2 of the first wall even if the critical neutron fluence accepted here is overestimated.

Accordingly, the amount of electricity generated over the service life is finite. Based on the fact that $C^{\mathrm{FW}} \sim C_n^{FE}$, the dollar value C^E of electricity generated from each square meter of the first wall is given by the relation

$$C^{E} = (566/3)\cdot10^{12}\cdot[1/(3600\cdot1000)]\cdot0.04 = \$2.1\cdot10^{6}/\mathrm{m}^{2},$$

where 1/3 is the conversion factor of P_{DT} fusion energy into electricity; 3600·1000 J – 1 kW·h; and \$/[0.04/(kW·h)] – cost of electricity.

This relation is a fundamental property of fusion energy: the lifetime of the first wall is directly related to the neutron energy transmitted through the material of the first wall and the amount of electricity generated. The resulting value $\$2.1\cdot10^6/\mathrm{m}^2$ is small. Regardless of the approach or work schedule, after such an amount of electricity is generated per square meter of the first wall the reactor must be shut down in order to be replaced.

Another fundamental property of a fusion reactor is that it does not consist of separate, independently replaceable "building blocks." Both general physics and the physics of fusion plasma are firmly related with the physics of the interaction of the plasma with the surfaces facing it.

Tokamaks with the best plasma parameters have complex and interconnected load-bearing structures of a vacuum chamber with its ports of toroidal, poloidal, and stabilizing coils, vacuum, heating and plasma control systems, and a blanket in the future. They are all 3-dimensional and interconnected in space. Stellarators, which are even more complicated, will additionally have a nonuniform neutron flux and damage to the first wall, reducing the life of the entire structure.

This complexity makes it virtually impossible to pay solely for the replacement of the first wall in a high-activated machine with the cost of electricity produced in a pure fusion DT-reactor, regardless of the cost of the first-wall materials and the expensive other needs discussed in [1]. At the same time, devices with a simpler (non-toroidal) geometry, which can cushion the described problem, still have insufficient plasma parameters.

In the absence of a fusion reactor on the horizon, for fundamental reasons the only option is to consider more efficient use of 14 MeV neutrons in combination with a fission blanket in hybrid reactors, proposed by A. D. Sakharov in the 1950s and then H. Bethe [2] and others in the 1970s. In this case such neutrons from the DT plasma only initiated fission reactions in the blanket, and the fission reactions produced the bulk of the energy. This approach would break the link of the neutron flux and the produced energy with the lifetime and unacceptable destruction of the first wall, which excludes the commercialization of pure thermonuclear fusion.

Hybrid reactors could possibly open up many areas for research on the combination of nuclear fission and fusion as noted in [1]. In particular, at the research stage they could determine to what extent nuclear fusion is compatible with nuclear power. Of course, hybrid reactors impose requirements that 'relaxed' fusion must fulfill. The most important necessary condition is reliable and safe burning of plasma with no disruptions, which has yet to be developed and demonstrated before any conceivable merging of fusion with nuclear energy.

Status of tokamak fusion. In 1994, the TFTR (USA) tokamak showed, for a fraction of a second, fusion power P_{DT} = 10.7 MW 50/50% from DT plasma, heated by injection of a 39.5 MW neutral beam (NBI) [3–5]. Note that the ion temperature 30 keV at plasma center, mentioned as problematic in article [1] (for the "neutron-free" D–He^3 reaction), was common in powerful TFTR discharges (called supershots) with improved plasma confinement which were obtained by coating the inside of the vacuum chamber with lithium. In some discharges it reached 45 keV. So, a high temperature in tokamaks is, in fact, a solved problem. Subsequently, in 1997, the JET tokamak (Great Britain) reached peak DT power P_{DT} = 16 MW in DT plasma [6, 7]. These two advances, widely regarded by the scientific community as significant advances in increasing plasma reactivity, have also highlighted major challenges in advancement towards efficient nuclear fusion. In particular, the power gain factor $Q_{DT} \equiv P_{DT}/P_{NBI}$ was 0.27 at TFTR and 0.67 at JET, and not the expected breakeven value Q_{DT} = 1 (here P_{NBI} is the absorbed power of 120 keV energetic DT-atom beams injected into the plasma).

The US Department of Energy took a different position – Q_{DT} = 0.27 in TFTR undermines confidence in tokamaks. As a result, the fusion energy program was transformed into a fusion science program, the United States withdrew from ITER, and the overall funding for thermonuclear research was significantly curtailed. Such a reaction clearly indicated the need to develop another more efficient approach to fusion before considering its energy issues.

This did not materialize. In Europe, lack of success with Q_{DT} = 1 did not affect national programs. An abbreviated version of ITER was developed using the same approach that suffered a setback in the mid-1990s. In the USA, the change in approach was reduced to changes in the form of the plasma, such as a compact stellarator (toroidal magnetic configuration with an axially asymmetric magnetic field) and a tokamak with a spherical plasma surface (which, in the meantime, turned out to be convenient for research). In 2003, the United States rejoined ITER.

A kind of milestone in fusion research is now approaching. In 2021, a second DT experiment will be performed on the JET tokamak (TFTR was dismantled 15 years ago) in the same regime that was unsuccessful in 1997. Being unable to obtain Q_{DT} = 1 or at least 0.67, as in 1997, this experiment will provide direct proof that the currently accepted approach to thermonuclear fusion is not capable of success. The reserves of the approach were exhausted 20 years ago. Even the announced plans for this second DT experiment with reduced $Q_{DT} < 0.4$ are doubtful. It is not difficult to predict that the credibility of the next-step ITER machine, which is simply a "big JET" with significantly more problems, will be severely undermined.

Actually, the impending setback for JET, which did not change its plasma regime after 1997, could have been expected 20 years ago – in 1998 it was realized that the improvement in plasma confinement, found in TFTR, when surfaces in contact with the plasma were covered with a layer lithium, indicates the possibility of both new plasma regimes and new approaches to thermonuclear fusion [8]. Experiments performed with T-11M tokamak on using lithium to pump out plasma made a key contribution to understanding the effect of lithium on plasma [9].

At the same time, it became clear that the 1951 Tamm–Sakharov approach to modern thermonuclear fusion has a fundamental deficiency. Their requirement for nested, toroidal, magnetic surfaces together with the V. D. Shafranov's

requirement of a strong toroidal field for plasma stability trully propelled tokamaks into the lead in terms of thermonuclear plasma parameters [10]. But, being insufficient for a burning plasma, this solved only part of the problem. For six decades a tokamak plasma remains in strong interaction with material surfaces (walls, receiving plates of the divertor). Energetic ions leaving the plasma hit material surfaces and turn into cold atoms. They return to the plasma boundary layer, the edge of the plasma. There they exchange charge with hot plasma ions, which exit the plasma as energetic atoms, and the process is repeated. Such recirculation of plasma particles, called recycling, is a powerful mechanism for cooling the plasma edge. It makes heating the plasma by external means ineffective.

Essentially, all plasma problems of tokamak fusion are associated with the cold edge of the plasma column [11]:

Cold edge	→ plasma edge temperature T^{edge} much lower than the core temperature: $T^{edge} \ll T^{core}$;
$T^{edge} \ll T^{core}$	→ turbulence → poor confinement of plasma energy;
Bad confinement	→ excessive heating power → more turbulence;
Bad confinement	→ large size, magnetic field, plasma current, and costly, inefficient devices;
Large plasma size	→ nearly impossible tritium fueling of the core zone of the plasma, negligible burnup of tritium;
Large plasma size	→ dangerous for the vacuum chamber power and heat loads from plasma disruptions, i.e., spontaneous termination of the discharge and decay of the plasma;
High heating power	→ unpredictable plasma and its interaction with material surfaces (PSI, Plasma-Surface Interaction), need for radiation from the plasma edge;
Plasma edge radiation	→ unpredictable plasma → disruption of stability, disturbances, internal damage to machines;
High heating power	→ unsolvable problem of energy extraction from plasma and numerous other technological problems;
$T^{edge} \ll T^{core}$	→ bad stability in the plasma core, low β (ratio of plasma thermal energy to magnetic energy);
$T^{edge} \ll T^{core}$	→ bad use of the plasma volume for burning DT;
…	→ list of properties incompatible with burning plasma is endless for such a regime.

It is really surprising that for six decades nuclear fusion has been trying to combat the powerful mechanism of plasma cooling via recycling by increasing the external heating power. This explains the reason for the failure of thermonuclear research in comparison with other areas of physics as noted in [1].

Some visible progress in thermonuclear fusion was made in 1982 after the discovery of the H-regime at the ASDEX tokamak (Germany) [12]. The H-regime almost doubles the energy retention time due to the use of a simplified magnetic geometry for the open divertor, which directs the particles emerging from the plasma onto special plastic targets, thus protecting the side walls around the plasma [13]. The H-regime was regarded as a shortcut to high-quality plasma without the complications of the pumping divertor proposed in the early 1970s [14].

In actual fact, four decades after its discovery the H-regime has not brought nuclear fusion closer to the minimum threshold $Q_{DT} = 1$. Within the existing approach nothing significant can be expected with or without the H-regime. Moreover, the H-regime with plasma edge temperature >2 keV, which is necessary for improved confinement, is incompatible with the divertor plate materials. Energetic ions from the plasma sputter their surface, leading to plasma disruptions. Solid materials are incompatible with the hot plasma edge needed to improve plasma confinement. This complicates the physics of a high-power tokamak, limits the parameters, and renders the plasma nonstationary and unstable. A second DT experiment on JET scheduled for 2021 with $Q_{DT} < 0.4$ planned, which is lower than in 1997, will confirm this characteristic.

The high turbulent heat conduction of the plasma via the electron channel renders energy confinement in the plasma and the temperature and density profiles inside the plasma volume poorly predictable. The layer of plasma located on open lines of force of a magnetic field immediately beyond the boundary of the main plasma confined by a magnetic field has an intricate physics of electric fields, plasma flows, impurities with a high atomic number, physics of radiation and other atomic processes. At the same time, this layer is of decisive importance for the stability of the plasma and the extraction of energy from it.

The low level of confinement in combination with the complex physics of energy losses from the plasma body, the physics of its boundary and its interaction with the wall render the plasma poorly controllable, and this is a feature of modern nuclear fusion. It relies exclusively on the large dimensions of research facilities, while at the same time accumulating technical and technological problems. Such plasma cannot be close to the overall or particular nuclear requirements noted in article [1]. Tritium burnup of 10%, mentioned as the minimum expected from thermonuclear fusion, is inconceivable for a high recycling regime applied to a burning plasma. It is impossible to deliver fuel to the central zone of the plasma column, the only zone in the plasma of this regime that effectively burns DT.

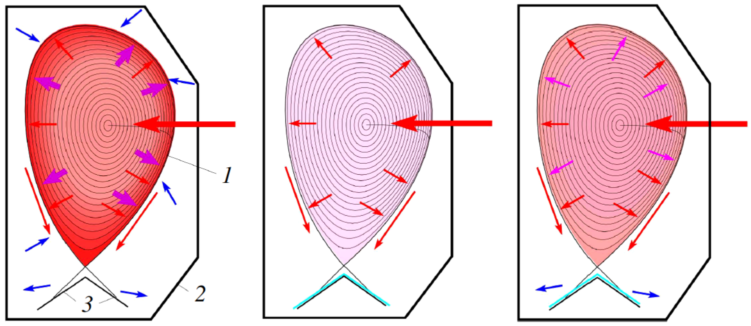
An unpredictable plasma core and plasma edge, full of complex physics, render highly recyclable plasma not only highly inefficient but also unreliable to control and prone to disruptions that terminate the plasma discharge. Malfunctions, inevitable due to the unpredictable near-edge physics of the plasma column, are unacceptable for installations with burning plasma. The current plasma regime in all aspects is clearly not suitable for either a pure fusion reactor or a hybrid idea.

Return of thermonuclear fusion to its original idea and general physics. The original idea of magnetic fusion is to isolate high-temperature plasma from the walls. To be consistent with it the Tamm–Sakharov approach must be supplemented by the requirement to suppress recycling and thereby cool the plasma by pumping out plasma particles going toward the wall. In turn this automatically requires feeding high-energy particles from neutral atom injectors deep into the interior of the plasma. This make-up fueling is unique in that it excludes the cooling of the plasma edge by the incoming fuel. Under these two necessary conditions – pumping plasma out from the periphery + feeding fuel into the central part of the plasma – the high-temperature plasma does not sense the presence of a wall as was incorporated into the initial idea of magnetic nuclear fusion. Technological means for both requirements exist: the liquid lithium flowing along the plasma contact zones (divertor receiving plates) can pump out plasma at any high temperature and any low density and injection of energetic atomic beams, well developed for fusion research and widely used in tokamaks as a heating method, can deliver energetic 80–130 keV particles to the central plasma zone. Lithium pumps out hydrogen isotopes more efficiently than any mechanical pump or solid surface. Lithium becomes liquid at moderate temperature 181°C and can transport the evacuated particles outside the vacuum chamber, while fresh particles replace them. In reality, the flow should be organized as a continuously flowing loop controlled by an electromagnetic pump. The idea of lithium pumping of plasma is rooted in the late 1960s, when lithium was tested in hydrogen beam experiments. In 1969 almost complete 100% confinement of ions in a hydrogen beam was measured in [15]. In [14] lithium plasma pumping was included in the design of one of the first thermonuclear reactors, UWMAK-1.

Make-up fueling solely with energetic atom injection requires much better plasma confinement times. In fact, low recycling and deep replenishment represent the best retention regime, which has an order of magnitude longer retention times than at present. This makes low recycling uniquely compatible both with plasma replenishment by injection of energetic atoms and with burning plasma, which can be shown even in the JET tokamak [11].

In the 1980s, the discovery of the H-regime pushed aside the idea of low recycling. But even during the last two decades, when a new concept of low recycling fusion was developed, it was not accepted by the thermonuclear community, who are fixated on an approach that already failed in the mid-1990s. Only experiments on small tokamaks CDX-U and LTX can be considered an exception.

At the most basic level, the essence of plasma confinement in tokamaks is explained in Fig. 1. Each position shows a toroidal cross-section of the plasma within the walls of the vacuum chamber. The closed contours represent the cross sections of the Tamm magnetic surfaces in the plasma volume. Outside it the magnetic field has open lines of force that terminate at the target plates of the divertor. Accordingly, the diffusion flux of charged particles from the nucleus (short red arrows in Fig. 1) goes to the plasma boundary. Behind it, charged particles are directed along the magnetic field to the divertor plates (long red arrows). In all three cases, the plasma is heated with the help of the injection of atoms with beam energy 120 keV, which is used in large tokamaks. Such injection provides both energy and particles to the entire volume of the plasma.



a *b* *c*

Fig. 1. Three plasma regimes determined by recycling: *a*) high recycling regime with complex physics of the plasma core, plasma leaving the confinement region interacts with the material surfaces with high, as a rule, atomic number, the plasma edge is cold, $T^{edge} \ll T^{core}$, the heat conduction is high, T^{core} is determined by the power P_{PBI}; *b*) idealized case of zero recycling with no plasma cooling, no energy losses due to heat conduction, $T^{core} = T^{edge} = E_{NBI}/5$, only the diffusion of particles determines the energy losses, the plasma density n^{core} is determined by the power P_{NBI}, instead of a plasma layer a simple flow of independent energetic particles from the plasma into the lithium is present behind the boundary of the main plasma; *c*) realistic case of low recycling ≅0.5 with $T^{edge} = E_{PBI}/10$, very low heat conduction losses and n^{core} losses, determined by P_{NBI}, plasma physics plays a very small role in the plasma parameters [performance]; *1*) toroidal section of the plasma; *2*) cross section of the vacuum chamber; *3*) divertor plates receiving the plasma.

Figure 1*a* shows the main processes in the high recycling regime with a significant inflow of cold particles from the wall (⟶). Recycling strongly intensifies the flow of cold particles: the particles can bounce backward and forward several times, thus cooling the plasma. The resulting large difference in plasma temperature between its center and periphery induces turbulence with anomalously high heat conduction and energy losses (➞). The plasma temperature *T* is determined by injection heating (or other sources). The energy of the beam particles (120 keV) is not related to the temperature of the plasma core. The physics of energy transfer from the core and a layer just outside the plasma boundary is complex. Such plasma is susceptible to disruption and is unacceptable for nuclear research.

Figure 1*b* shows the opposite idealized case of no recycling. Recycling is quantitatively expressed by the coefficient *R*, equal to the flux $\Gamma^{w\to e}$ of cold particles reflected from the wall to the edge of the plasma divided by the incident flux $\Gamma^{e\to w}$ from the plasma to the wall:

$$R \equiv \Gamma^{w\to e}/\Gamma^{e\to w}.$$

Here "wall" means all material surfaces in contact with the plasma, including the receiving plates of the divertor. In the absence of plasma pumping by the wall, the coefficient is equal to 1, as at present. On complete absorption of the plasma flow, the recycling is equal to 0. The physics of plasma with zero recycling is simple. The atoms of hydrogen isotopes in the injected 120 keV beam carry energetic ions and cold electrons. After capture of the atomic beam, due to charge exchange and ionization in the plasma and subsequent thermal relaxation the energy of the atomic beam 120 keV is converted into the plasma energy equally distributed over the particles with temperature 24 keV (120/5). Then, plasma particles from the core diffuse to the edge. After crossing the plasma boundary they fly at speed equal to about 1000 km/sec along magnetic field lines to the absorbing lithium layer. There are no cold particles in the entire system. Plasma does not sense the presence of material surfaces. The plasma temperature will be 24 keV everywhere automatically. This regime, which is hypothetical but based on rigorous science, would have realized the original idea of magnetic fusion.

Moreover, this mode is controlled exclusively by the laws of general physics. The mentioned processes are consistent with well-known and reliable general physics. The two most wasteful research topics in magnetic fusion – turbulent heat conduction in the plasma core and the complexity of the interaction of plasma with material surfaces – simply do not exist. For six decades they dominated nuclear fusion research, producing nothing useful for producing burning DT plasma other than large and costly projects.

The intermediate regime – position b with recycling level *R* = 0.5 – is realistic in combination with plasma pumping by liquid lithium. A low lithium flow rate 1 g/sec (2 cm^3/sec) is sufficient to pump out the tokamak plasma. This critical

number, corresponding to a thin (0.1 mm) lithium layer moving at a speed of less than 1 cm/sec, makes its flow compatible with the strong magnetic field of tokamaks. Such a flow, driven by gravity along a wetted surface, is insensitive to electromagnetic forces in the tokamak, including those associated with disruptions. It can be implemented in virtually any tokamak.

The regime with $R \cong 0.5$ in position c is much closer to zero recycling than to the current high-recycling situation. We shall explain this in detail. The injection of energetic atoms gives a flux $\Gamma_{\mathrm{NBI}} = P_{\mathrm{NBI}}/E_{\mathrm{NBI}}$ of energetic ions and low-energy electrons. In the stationary phase of the discharge, the same particle flux leaves the volume to the edge of the plasma $\Gamma^{e\to w} = \Gamma_{\mathrm{NBI}}$. Two streams of particles fall from the outside onto the edge of the plasma and return to the wall. One of them Γ^{g} is associated with a possible shot (injection) of gas, the second one $R\Gamma^{e\to w}$ consists of particles reflected from the wall. All three taken together are equal to the flux from the edge of the plasma to the wall:

$$\Gamma^{e\to w} = \Gamma_{\mathrm{NBI}} + \Gamma^{g} + R\Gamma^{e\to w},$$

which is equivalent to the following expression for the particle flux onto the wall:

$$(1 - R)\Gamma^{e\to w} = \Gamma_{\mathrm{NBI}} + \Gamma^{g}$$

or

$$\Gamma^{e\to w} = \Gamma_{\mathrm{NBI}} + \Gamma^{g}/(1 - R),$$

which clearly shows particle flux enhancement by recycling when it is close to 1. This flux carries the energy absorbed in the volume from the edge of the plasma to the wall:

$$5/2\Gamma^{e\to l}(T_e^e + T_i^e) = P_{\mathrm{NBI}} + P_{\alpha\text{–rad}}.$$

Here T_e^e and T_i^e are, respectively, the temperature of electrons and ions at the plasma boundary; $P_{\mathrm{NBI}} + P_{\alpha\text{–rad}}$ is the power delivered to the plasma from the injection of atomic beams and α-particles from DT reactions minus synchrotron radiation and bremsstrahlung. The last relation sets the temperature of the plasma edge expressed in terms of the global parameters of the plasma regime: heating power and particle fluxes, as well as the recycling coefficient in the form

$$(T_e^e + T_i^e)/2 = (1 - R)(E_{\mathrm{NBI}}/5)(1 + P_{\alpha\text{–rad}}/P_{\mathrm{NBI}})/(1 + \Gamma^{g}/\Gamma_{\mathrm{NBI}}),$$

where the relation $P_{\mathrm{NBI}} = E_{\mathrm{NBI}}\Gamma_{\mathrm{NBI}}$ shows the role of the injection energy E_{NBI} in the plasma temperature. Note that any kind of shot of gas, including lithium powders or dust, granules, jets, intentional or unintentional, is undesirable. It cools the edge of the plasma.

Based on the laws of general physics, it is shown here that the temperature of the plasma edge does not depend on the internal properties of the plasma, such as the thermal conductivity and diffusion, or their turbulent nature. This clearly shows that in the current approach to nuclear fusion with $R \sim 1$ the temperature of the plasma edge is low regardless of the heating power. The slightly raised temperature of the plasma edge in the H-regime is due to a slight reduction in recycling due to cleaning of the walls with some ability to temporarily absorb hydrogen isotopes and the use of high heating power.

In contrast, with realistic recycling $R = 0.5$, the edge temperature is only 2 times lower than with ideal zero recycling and incomparably higher than in H-regime. An important property is that the temperature of the plasma edge is high and is determined directly by the energy of the injected beam, and not by the power. The temperature in the plasma core cannot be lower than at the edge (tokamak radiation is weak), which makes plasma fed by a 120 keV DT beam ready for burning.

Detailed information about this, based on a general physical approach to thermonuclear fusion, is given in [11], where the 0.5 recycling regime with $Q_{\mathrm{DT}} > 5$ is simulated numerically for the JET tokamak (see Table 1).

In contrast to the generally accepted high-recycling regime [3, 4, 6, 7] the presented LiWFusion-regime for JET predicts $Q_{\mathrm{DT}} > 5$ with a tritium burnup fraction >7%, injection power $P_{\mathrm{NBI}} = 3$–4 MW (32 MW installed) with 120 keV beam, standard (for JET) plasma current $I_p = 3$ MA, and a toroidal field $B_t = 3$ T. The predicted parameters of burning plasma with low recycling are insensitive to the input parameters for $R < 0.5$.

The calculations were performed under conservative assumptions, including nearly infinite thermal conductivity of electrons and particle diffusion coefficient 60 times higher than the neoclassical theory. Only a fraction of the energy of α-particles is assumed to be released in the plasma core (about 83% of their orbits remain in the plasma before collisions,

TABLE 1. Thermonuclear Parameters of Plasma with Low Recycling 0.5 JET: $B_t = 3$ T, $I_p = 3$ MA, $R/A = 3$, Recycling 0.5

No.	P_{NBI}, MW	E_{NBI}, keV	P_{DT}, MW	Q_{DT}	Tritium burnup fraction, %	Beam power release profile	α-Particle energy fraction for plasma heating
1	4.06	120	25.9	6.39	8.72	Parabolic	50
2	3.02		17.5	5.81	7.92		
3	4.0		21.7	5.43	7.40	Concave	
4	2.99		16.3	5.44	7.42		
5	4.01	100	19.0	4.74	5.39	Parabolic	
6	3.0		15.4	5.13	5.83		
7	4.0		18.8	4.69	5.33	Concave	
8	3.0		13.5	4.48	5.10		
9	3.1	120	24.6	7.94	10.8	Parabolic	75

which gives an additional reserve for plasma heating). Conventional, highly recyclable plasma simply could not exist under these assumptions.

In the LiWFusion regime, heat conduction in the interior of the plasma does not play a significant role, even if it is turbulent and arbitrarily large. Energy losses are mainly due to particle diffusion. Plasma radiation is very weak. It is useful for directing some of the thermal energy to the side walls instead of the divertor plates. All this leads to a small 3–4 MW of absorbed injection power instead of 40 MW in TFTR and in the planned DT experiment at JET. Accordingly, Q_{DT} greatly exceeds 1.

According to simulation, the burnup fraction of the tritium introduced into the plasma is ≅10%. In [1] this low level was wrongly attributed to contemporary nuclear fusion, which is unlikely to reach 0.1%. Flowing lithium, absorbing hydrogen isotopes from the plasma, delivers unburned deuterium and tritium to a compact external vessel with lithium. The subsequent recovery and reuse of unburned fuel becomes a practical ~~solution to the~~ problem. The technology of flowing lithium will most likely make tritium recuperation possible in real time with return ~~into the energetic-beam injection~~ system. This would remove the problem [1] of the ~~degree of~~ tritium burnup, which per se is expected to be high. Recuperation is problematic in the contemporary concept: tritium makes up a small fraction of the gas mixture pumped out of the plasma, which must be sent through pipelines to a separate tritium plant to separate tritium, which complicates, slows down, and increases the cost of the entire process.

Without delving into deeper details another critical property of the low recycling regime must be noted. Its plasma is fully controlled by external means (energetic beam injection system and standard configuration control) and is predictable. This is necessary to prevent plasma disruptions, which have remained out of control since their discovery in tokamaks in 1963. Low recycling regimes raise the hope that this obstacle to future fusion applications will be removed.

Conclusion. So, the article [1] was supplemented here with an argument about the impossibility of a pure thermonuclear power reactor: it is impossible to cover the cost of the first wall damaged by 14 MeV neutrons by ~~using~~ electricity obtained from thermonuclear fusion. The relation between the lifetime of materials and the energy produced is a fundamental property of thermonuclear fusion.

The plasma-~~physical~~ roots of the failure of magnetic fusion were also shown here. The current situation in the fusion sphere is worse than described in [1]. The upcoming DT experiment on JET, the best thermonuclear machine, will be proof of failure of the current decades-long approach. Rigorous science has essentially been replaced by interpretations, often false even in the critical aspects of fusion. One example is that recycling, which is the main effect in plasma energy losses, has been ignored in confinement theory. As an alternative to the plasma physics-driven approach exhausted in the 1990s a new concept of thermonuclear fusion was created based on tokamaks and general physics. Unlike plasma physics, it is reliable and predictive. Two large parts of tokamak physics – turbulent heat conduction and ~~build-up of complex~~ effects at the plasma boundary

layer interacting with material surfaces (which impeded progress on tokamaks) – can be eliminated from consideration. Being independent of these parts, the low recycling concept offers real prospects for the development of reliable plasma that meets the requirements of thermonuclear burning.

The new approach is based on existing machines and their equipment operating under much less stressful conditions without the need for 30–40 MW of heating power (like TFTR and JET), which creates technical difficulties. The new concept is simple and mature enough for implementation in the JET tokamak. The expected extension of its service life by four years after the DT experiment in 2021 gives enough time to prepare the machine for a demonstration of a real burning plasma with parameters close to those given in Table 1.

Technically, some additional design and technology development has to be done for the JET 0.5-recycling divertor. Most of the work does not require access to the tokamak and can be performed in a separate test setup with a vacuum chamber.

Success, much more predictable than current fusion plans, will open the way to the next step in fusion, i.e., the creation of a 100–200 MW fusion-fission research facility (FFRF) with reasonable toroidal plasma size $R/a \sim 4$ m/1 m and a 1 m thick blanket to study the possibility of combining the approaches of nuclear fission and thermonuclear fusion for energy without CO_2 release [1]. This step necessitates additional development of a technology for pumping helium, which was not discussed here. It is not essential for short plasma bursts in JET but should be developed as more experience is gained with low recycling regimes. An FFRF capable of achieving thermonuclear DEMO with demonstration of $Q_{DT}^{E} > 1$ sufficient for producing more electricity than is consumed would be aimed at the practical goal of studying fission in combination with fusion for energetics. Such a facility would provide real soil for making assessments of the place of thermonuclear fusion in nuclear energy, which V. V. Orlov and article [1] initiated.

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