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Igniting a microexplosion by a microexplosion and some other controlled thermonuclear fusion scenarios with neutronless reactions

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Contents

Abstract. Several proposals for the power production application of neutronless fusion reactions and the $\mathrm{D} + \mathrm{D} \to {}^3\mathrm{He} + \mathrm{n} + 3.27$ MeV reaction are reviewed. Compressing low-tritium fuel by thermal radiation from one or more D–T microexplosions possibly combined with one or more drivers is considered as the optimum ignition strategy for microexplosions with physically important D–D fusion reactions. Results are presented that show the incorrectness of three assumptions that the ignition of the $\mathrm{p} + {}^{11}\mathrm{B} \to 3\alpha + 8.9$ MeV reaction can be facilitated by chain reactions. The delivery of lunar ^{3}He as a thermonuclear fuel component for large-scale power production on Earth is discussed from the standpoint of expediency.

Keywords: controlled thermonuclear fusion, neutronless fusion reaction, DD fusion, igniting a microexplosion by a microexplosion, lunar helium-3

1. Introduction

Problems related to controlled thermonuclear fusion (CTF) have been under discussion for no less than 86 years. Gamov recollected that in 1932, N A Bukharin, who headed the Research Sector of the Supreme Soviet of the National Economy of the USSR (VSNKh) from 1929 through 1932 and the Research Sector of the People's Commissariat of Heavy Equipment Industry of the USSR from 1932 through 1935, proposed that he [Gamov] "head a project to develop controlled thermonuclear reactions" (see, e.g., [1]). The physical idea underlying the project was to pass electric current "through a very thick copper wire stuffed with tiny 'bubbles' containing a lithium–hydrogen mixture" [1]. Gamov recollected as well that Bukharin understood that the project required significant resources. It was stipulated that in performing the project, Gamov "will have available the total electric power of the Moscow industrial region for several minutes one night a week" [1]. Gamov "declined the offer and was happy that he made that decision, since the project was doomed to fail" [1]. Bukharin's proposal actually involved igniting neutronless reactions

$$\mathrm{p} + {}^6\mathrm{Li} \to {}^3\mathrm{He} + \alpha + 4\ \mathrm{MeV}\,, \qquad (1)$$
$$\mathrm{p} + {}^7\mathrm{Li} \to 2\alpha + \gamma + 17.3\ \mathrm{MeV}$$

and four reactions between deuterons and lithium isotopes, of which two are neutronless (see [2–4]).

Modern-day CTF studies are primarily focused on deuteron–tritium (DT) fusion:

$$\mathrm{D} + \mathrm{T} \to \alpha + \mathrm{n} + 17.58\ \mathrm{MeV}\,. \qquad (2)$$

The main advantage of this reaction is that it can be ignited in a facility with nondisposable structure elements located at a

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distance of several meters or less, much more easily than any other reaction. Nevertheless, exploring options for efficient implementation and, eventually, practical use of other reactions is of significant interest. One reason, which is sometimes considered the primary one, is that 80% of the energy in reaction (2) is output in the form of the neutron's kinetic energy. We quote a statement made by Feoktistov [3] (see also his *Selected Works* [4], p. 152 and 153): "It should be said that the issue of neutronless reactions has been repeatedly raised in publications [10] (reference [10] in [3] corresponds to reference [5] in this paper — M L Sh). The point is that the reactions that are available most easily may not be fully considered as 'clean' ones. They are accompanied by a strong flux of neutrons: 14 MeV neutrons from the DT reaction may interact in a plethora of ways with virtually any substance by means of (n, 2n), (n , γ), (n, p), etc. reactions. The induced radioactivity cannot be completely eliminated; it can only be reduced by properly selecting structural materials. This factor is of special importance since the yield of neutrons in the reactions with hydrogen isotopes is five times larger than in fission (mentioning the neutron bomb would be quite relevant here)." According to Semenov [6], "even if the thermonuclear fusion of tritium occurs, it proves to be no more promising that the breeder reactor method due to its disadvantages. Therefore, practical implementation of the T + D reaction should only be regarded as a step towards solving the problem on the basis of the D + D reaction ... implementation and engineering design of power generation facilities on the basis of the T + D reaction seem to be of paramount importance for the future implementation of D + D [reaction]" [6].

The problems with practical use of several neutronless reactions are similar to those of the neutron-generating reaction

$$\mathrm{D} + \mathrm{D} \rightarrow {}^{3}\mathrm{He} + \mathrm{n} + 3.27\ \mathrm{MeV}\,. \tag{3}$$

In another deuteron–deuteron (DD) fusion reaction,

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T} + \mathrm{p} + 4.03\ \mathrm{MeV}\,, \tag{4}$$

neutrons are not released; however, according to most scenarios for using reactions (3) and (4), the tritium it generates participates in reaction (2) with a significant probability, often close to unity.

Processes (3) and (4) are described in studies as either different DD-fusion reactions or different branches of the same reaction; their probabilities are approximately the same [7]. The DD-fusion reactions are referred to in book [7, p. 27], where both versions of the terminology are used, as "the most desirable reaction in the sense of a virtually unlimited supply of inexpensive fuel, easily extracted from the ocean."

The range of opinions regarding the use of neutronless reactions and reaction (3) for power generation is very broad. On the one hand, Scott argues, concluding his article [8] published in 2005, "If fusion is to be developed as a world energy source this century, there is no realistic alternative but to face and solve the problems of burning DT — in particular by developing low-activation structural materials." On the other hand, some studies including recent ones (see, e.g., [9–22]) explore options for using the reaction

$$\mathrm{p} + {}^{11}\mathrm{B} \rightarrow 3\alpha + 8.9\ \mathrm{MeV} \tag{5}$$

for power generation and the expediency of delivering lunar ^{3}He to Earth for large-scale use in the world's power generation system as a fuel component in the reaction

$$\mathrm{D} + {}^{3}\mathrm{He} \rightarrow \alpha + \mathrm{p} + 18.34\ \mathrm{MeV} \tag{6}$$

(see, e.g., [8, 11, 23–35] and the references in [8, 24]).

Some problems related to the feasibility and expediency of using reactions (3)–(6) for power generation are considered below. Other areas where thermonuclear reactions could be used for peaceful purposes (see, e.g., [4, 10, 26–33]), are beyond the scope of this paper.

2. Explosive deuterium power generation

In analyzing Stott's statement quoted in Section 1, we should take into account that all calculations reported in [8] refer to magnetic plasma confinement.

The method for using reactions (3), (4), and (6) to generate electric power, which is the simplest from the engineering perspective, is analyzed in detail in book [34]. It is based on initiating deuterium explosions, i.e., thermonuclear explosions that occur as a result of compressing and heating of deuterium with nuclear explosions. The blasting charges, i.e., the devices that trigger the nuclear and subsequent thermonuclear explosion, should explode in a chamber named the "explosive burnout vessel" (EBV) by the authors of [34]. The vessel casing is protected from the blast with liquid sodium, which also performs as a heat-transfer medium and de facto an additional fuel that significantly enhances energy release; the electric power itself is generated by steam turbines [34]. Some of the neutrons generated by the blast are used to produce fissionable materials (^{239}Pt from ^{238}U or ^{233}U from ^{232}Th), which are used, in turn, for manufacturing new blasting charges and as a fuel for nuclear reactors [34]. Energy generation technology based on the concepts under discussion is described in terms of "explosive deuterium power generation" (EDPG) and "EBV power generation" [34].

Because reactions (3) and (4) generate 'secondary' ^{3}He and tritium, and the parameters of the plasma generated by the deuterium blast are favorable not only for those reactions alone but also for reaction (6) and, to an even greater extent, reaction (2), these reactions make a significant contribution to energy release in the blast [34]. Other nuclear reactions also occur in such a plasma, including the splitting of a deuteron by a neutron, which requires 2.2 MeV of energy [34]. As a result, the total balance of deuteron burning in the explosion can be approximately represented as

$$7\mathrm{D} \rightarrow 2\alpha + 3\mathrm{p} + 3\mathrm{n} + 41\ \mathrm{MeV}\,, \tag{7}$$

while if reactions (2)–(6) alone are taken into account, the complete burnout of 'secondary' ^{3}He and tritium yields [34]

$$6\mathrm{D} \rightarrow 2\alpha + 2\mathrm{p} + 2\mathrm{n} + 43.2\ \mathrm{MeV}\,. \tag{8}$$

The energy release from deuteron burning in the EBV is complemented by the energy release from other nuclear reactions and, primarily, fission (both instantaneous and accompanying the decay of slowed fission fragments) and the capture of neutrons by ^{23}Na with the production of ^{24}Na and the subsequent decay of ^{24}Na with the production of the stable isotope ^{24}Mg. The contribution of the last two reactions is very important: the energy release per captured neutron is $E^{\mathrm{n}}_{\mathrm{Na-Mg}} \approx 12.5$ MeV [34, 35], and hence the additional energy release pertaining to process (7), if all neutrons are captured, is approximately 37.5 MeV. In the example presented in [34, § 5.2], the explosion of a single

blasting charge that causes the 'burnout' of 50 g of ^{233}U and 100 g of deuterium results in the release of approximately 3.9×10^{13} J directly in the process of explosion (the contribution of thermonuclear reactions to this value is about 90%), 3.1×10^{13} J as a result of neutron capture by sodium (the output of fusion neutrons is 120 times larger than the output from uranium), and approximately 3×10^{11} J as a result of the decay of decelerated fission fragments. It may be reasonable in some situations to add the tritium produced as a result of previous explosions to blasting charges [34].

The authors of [34] claim that "the availability of a blasting charge prototype is the decisive advantage of EDPG over other concepts of global power generation," and "the engineering and technology problems that can be forecast in discussing EDPG have already been or can be resolved by humankind," and assess that the EBV return of investment timeframe is "four to five years after commencement of operations."

Power generation using nuclear and thermonuclear explosions has been discussed in other studies (see, e.g., the references in [34, 36, 37]). In our opinion, an approach like this is currently unacceptable for political reasons [38, 39].

The EBV is not a kind of CTF in the standard meaning of the term. It is of interest, however, that this approach formally does not disagree with the definition presented in [40], according to which CTF is "a process of fusion of light atomic nuclei that occurs with energy release at high temperatures and under controllable conditions." A brief description of the EBV concept is included in this review for the following main reasons. The data in book [34] show that power can be generated using large pulsed energy release in a chamber whose walls are protected with a liquid low-melting metal. This is of paramount importance for analyzing the feasibility of plans to build power generation facilities operating on the basis of powerful microexplosions or a series of microexplosions occurring with a small time interval. Those data show that in situations where it is not necessary to use almost all fusion neutrons to breed tritium, it is also helpful that some neutrons are captured by sodium. The feasibility of developing power generation facilities that feature the characteristics described above is discussed in Section 4.

3. Fuel for microexplosions with physically important D–D and D–^{3}He reactions

Some studies explored power generation using thermonuclear microexplosions with physically significant reactions (3) and (4) (see, e.g., [6, 10, 33, 38, 39, 41–50]). Those reactions will be of importance from the physical perspective if they make a significant contribution to the total microexplosion energy release Y both directly and through energy release in reactions (2) and (6) with the participation of 'secondary' tritium and ^{3}He. If the target is designed in an optimal way and actuates successfully, the thermonuclear burning of 'secondary' tritium will provide the main contribution to Y, while the fraction of the 'secondary' ^{3}He burning out in the blast and hence the relative contribution of reaction (6) to Y will be highly dependent on the fuel mass m_{fuel}, its characteristic density at the maximum compression stage ρ, and other factors [10, 42, 44–46].

Collection of the 'secondary' ^{3}He escaping from the region of fusion reactions in power generation facilities with both inertial and magnetic plasma confinement is of interest in and of itself (see, e.g., [8, 33, 41–43, 45, 51–53]). The primary fuel for the microexplosions regarding its mass and contribution to Y is either pure deuterium or a DT mixture with a small average atomic fraction of tritium $\langle x_{\text{T}}^{\text{main}} \rangle$ or a D–T–^{3}He mixture with small values of $\langle x_{\text{T}}^{\text{main}} \rangle$ and average atomic fraction of ^{3}He $\langle x_{^3\text{He}}^{\text{main}} \rangle$ (both homogeneous and inhomogeneous mixtures can be used; in the former case, the symbol for average in the notation for the atomic fractions of T and ^{3}He is omitted in what follows) [6, 10, 33, 38, 39, 41–50].

A requirement for the efficient use of such microexplosions in the setup of an approximately spherically symmetric implosion of fuel is that the product ρr, where r is the characteristic radius of the primary fuel at the maximum compression stage, must be no less than approximately 10 g cm^{-2} [10, 43, 45, 49]. For comparison, the minimum ρr value that enables efficient use of DT microexplosions (those in the plasma of which reaction (2) alone occurs) has recently been considered to be about 3 g cm^{-2} [46, 49, 54]; it was assumed previously that it could be approximately 2 g cm^{-2} [10]. The demanding requirements set for ρr translate into relatively demanding requirements for the energy needed to compress the fuel [10, 43–46, 49]. The difficulties associated with attaining high ρr values will be compensated, at least partly, by transferring a noticeable part of the kinetic energy of neutrons to the fuel and decreasing the relative contribution of reaction (2) to Y, thus allowing a reduction in the effect of neutrons on the structural elements of the power generation facility subject to irradiation with neutrons (see [45]).

Some studies also discussed power generation using microexplosions with a noticeable contribution of reaction (6) to Y if a significant amount of ^{3}He is directly added to the fuel [43, 44, 46, 49]. It was proposed to suppress the generation of neutrons, for example, by depleting the content of deuterium in the main fuel or, in other words, using the main fuel with $\langle x_{^3\text{He}}^{\text{main}} > 0.5$ [43].

To ease the initiation of microexplosions discussed here, it is reasonable to arrange conditions under which thermonuclear burning begins in a region with a relatively large atomic fraction of tritium x_{T}^{hs} (this region is sometimes referred to as a seed), which is in contact with the primary fuel [41, 43–45, 48, 49]. The superscript hs indicates that the corresponding parameter refers to the region where thermonuclear burning begins or, in other words, in the region where a hot spot is created. The optimal values of x_{T}^{hs} and the seed shape are determined by the selected process in which the hot spot is created and by $\langle x_{\text{T}}^{\text{main}} \rangle$ [45, 48]. In some studies, the optimization problem is not discussed; the value of x_{T}^{hs} is either set equal to 0.5 [45] or not specified (it is presumably implicitly assumed that x_{T}^{hs} is also 0.5) [41, 43, 49].

In a setup explored in [45], the seed extends to the lateral surface of the sphere formed by the seed itself and the main fuel, which consists of pure deuterium or a homogeneous DT mixture, and the hot spot is created in the fast ignition regime, i.e., as a result of heating the region where it is formed using an additional energy source (see also [4, 47–49, 55–57]). Numerical simulation showed that if $x_{\text{T}}^{\text{main}} \leqslant 0.01$, the value $x_{\text{T}}^{\text{hs}} = 0.2$ ensures an enhancement of the target gain G, i.e., the ratio of Y and the energy E_{t} delivered to the target to initiate the microexplosion, by 20% to 30% compared to the case $x_{\text{T}}^{\text{hs}} = 0.5$, while for $x_{\text{T}}^{\text{main}} > 0.01$ the dependence of G on x_{T}^{hs} is weaker [45].

In [44], the situations were analyzed where the hot spot is created as a result of spherically symmetric isobaric compres-

sion of fuel, which corresponds to the seed located in its center, at $x_T^{hs} = 0.5$, a small value of x_T^{main}, and $x_{^3He}^{main} = 0$ or $0.42 \leqslant x_{^3He}^{main} \leqslant 0.5$. It is assumed then that the main fuel with $x_{^3He}^{main} \neq 0$ contains 50% deuterium, ^{3}He, and tritium; for example, the value $x_{^3He}^{main} = 0.42$ corresponds to the composition $D_{0.5}{}^3He_{0.42}T_{0.08}$ [44]. One of the results reported in [44] is the choice of a small and fixed amount of tritium to be distributed to ensure the maximum possible G, if the hot spot is created due to the compression of the fuel. If a significant amount of ^{3}He is used in the fuel, tritium should be concentrated in the seed, while in the case of fuel that only consists of a small amount of tritium and deuterium, part of that tritium should be used in the seed, and part should be distributed across the main fuel [44]. It is apparently assumed here that although the amount of tritium is small, it is nevertheless larger than the amount required to create a seed with a minimum permissible mass. The conclusion regarding the efficiency of concentrating a small amount of tritium in the seed in the case of large $x_{^3He}^{main}$ and spherical or nearly spherical symmetry of the compression of fuel with the seed located in the central region seems to also hold if the hot spot is created in the fast ignition regime (see [49]).

A homogeneous fuel without a seed surrounded by an inert shell (referred to as tamper) with the composition $D_{0.99}T_{0.01}$ or $D_{0.495}{}^3He_{0.495}T_{0.01}$ was explored in [46]. The apparent advantage of targets with a fuel like this is their relatively simple design. Nevertheless, the issue of their efficacy for generating power, even if the fuel is compressed using the methods discussed in Section 4, is not clear because very large values $\rho r \geqslant 40$ g cm^{-2} are then needed. For example, a model situation is discussed in [46] with $\rho r = 40$ g cm^{-2} and $E_t = 160$ MJ (it is assumed that this entire energy is used to compress the fuel and heat it as a result to a temperature needed to ignite thermonuclear burning.)

For the sake of completeness of our review of proposals regarding fusion targets containing significant amounts of deuterium and reduced amounts of tritium, we note that using a homogeneous deuterium–tritium mixture with the atomic fraction of tritium $x_T < 0.5$ has been discussed in some studies as a fuel for DT microexplosions [58–60]. The values $x_T = 0.3-0.4$ and compression parameters close to the characteristic parameters of compression of an equimolar DT mixture of the same mass were considered in [58–60]. It was assumed that if $x_T \approx 0.3-0.4$ is chosen instead of 0.5, the reduced amount of tritium in the fuel and hence diminished turnover of tritium can justify a slight reduction in Y that corresponds to fixed E_t [58–60]. Switching from $x_T = 0.5$ to $x_T = 0.3$, i.e., a 40% reduction in the content of tritium as a result of which Y only reduces by 16% was analyzed in [58]. An approach like this may prove to be useful for both initiating microexplosions for academic research and generating electric power at some stage of development of the thermonuclear power generation industry.

4. Compressing fuel by and with the use of the thermal radiation of a deuterium–tritium microexplosion

4.1 Expediency of initiating microexplosions by or with the use of microexplosions

A subject of broad discussion is the option to compress fuel for microexplosions with physically important reactions (3), (4), and (6) exclusively by means of the energy delivered to the target by a laser or another driver, i.e., a device that affects the target to initiate a microexplosion (see, e.g., [10, 41, 43–49, 60]). The strict requirements for ρr result in strict requirements for E_t, the value of which must be significantly larger than that for initiating DT microexplosions even if fast ignition is used [10, 41, 43–49, 60]. An increase in E_t apparently results in an increase in the driver cost, which eventually may make electric power production unfeasible. Nevertheless, it is argued in [41] that reactions (3) and (4) and subsequent burning of 'secondary' tritium and ^{3}He is not impossible in commercially operated first-generation thermonuclear power generation plants.

Another method for attaining high ρr values is to compress the fuel with DT microexplosions initiated by a driver with moderate characteristics or several DT microexplosions [3, 4, 27, 28, 33, 38, 39, 42, 50]. It may be reasonable in some cases to compress the fuel "with the use of one or more DT microexplosions," i.e., one or more DT microexplosions that ensure the main compression and one or more drivers that improve the symmetry and time profile of the compression [31, 33, 38, 39, 50, 61].

The simplest and most efficient approach seems to be the complete or primary compression of fuel with a small or zero value of $\langle x_T^{main} \rangle$ with thermal X-ray radiation from one or more DT microexplosions, also performed by means of indirect compression of fuel, i.e., caused by thermal X-ray radiation [3, 4, 28, 33, 38, 39, 42, 50]. This technique will probably allow using reactions (2)–(4) and (6) for power generation with E_t of the order of 1 MJ, a value that corresponds to initiating a DT microexplosion with $Y \approx 1$ GJ or less, at least if fast ignition is used [3, 4, 38, 39, 50]. For example, it is claimed in the abstract of [3] that such methods provide opportunities for unlimited energy enhancement "with moderate input of energy for initiation (of the order of megajoules)." We emphasize, however, that failed attempts to initiate DT microexplosions at the NIF (National Ignition Facility) that have been made up to now (see, e.g., [47, 62–66]) prompt a guess that the theoretical estimates of E_t for DT microexplosions and any other microexplosions are only valid up to a factor that is, at best, in the range 0.5 to 2.0.

Proposals to compress fuel with a small or zero value of $\langle x_T^{main} \rangle$ by focusing the shock wave or plasma created by DT microexplosions [27, 28] are of interest mainly as a matter of history.

4.2 Main processes and characteristic values of their quantitative parameters

In what follows, we discuss the processes that are most important for the complete or main compression of fuel with thermal radiation of DT microexplosions and the characteristic values of the parameters that describe those processes. We only consider the setup where a single DT microexplosion compresses a fuel capsule (a structural unit whose main components are a fuel and an ablator, i.e., a material whose ablation causes compression of the fuel), and the symmetry of the compression process is nearly spherical. Other setups are analyzed in [3, 4, 28, 29, 31, 42, 61]. The fuel capsule compressed by the microexplosion is referred to as the 'secondary' capsule in what follows.

4.2.1 Energy and temperature of thermal radiation from a DT microexplosion and an example of the geometry of 'secondary' hohlraum. We let E_{rad}^{DT} denote the energy of the thermal radiation generated by a DT microexplosion and η_{rad}^{DT} denote

the ratio of $E_{\rm rad}^{\rm DT}$ to the energy release it causes. According to [10], the value of $\eta_{\rm rad}^{\rm DT}$ for a complex composite target with a DT fuel can be as large as approximately 0.2; the temperature of the radiation generated by that microexplosion falls in the range 300–1,000 eV. We note that the energy release in the microexplosion mentioned in [10] in relation to the quoted parameters is 100 MJ; it is assumed that the microexplosion is initiated by beams of light-element ions. The term 'complex composite target' means that the target contains not only a fuel capsule but also other structural elements [10]. This term is also applicable to targets with indirect compression of fuel whose capsule is placed into a cavity (or 'hohlraum', the term used to describe the shell surrounding the cavity) with the walls lined with an element with a large atomic number Z or a material that consists of more than one such element (see, e.g., [29, 31, 47, 49, 50, 54, 60–74]). The hot spot can be generated in targets with an indirect compression of fuel both as a result of compression and in the fast ignition regime [29, 31, 47, 49, 50, 54, 60–74]. According to [73, 75], the value of $\eta_{\rm rad}^{\rm DT}$ for targets with the indirect compression of fuel can be as large as 0.22–0.25 in accordance with the data in [10] quoted above.

If a secondary fuel capsule is compressed by microexplosion radiation, part of that radiation must be contained in another ('secondary') hohlraum, whose shape and size must, in particular, ensure sufficiently symmetric irradiation of the secondary capsule and sufficiently weak heating of the fuel it contains by microexplosion neutrons [3, 4, 29, 31, 50, 61]. These requirements can be satisfied [3, 4, 29, 31, 50, 61].

We assume that the driver initiates a DT microexplosion with

$$Y = 1 \text{ J} \tag{9}$$

and $\eta_{\rm rad}^{\rm DT} = 0.25$; the inner walls of the secondary hohlraum are made of gold; the secondary fuel capsule absorbs thermal radiation with the energy

$$E_{\rm c} = 20 \text{ MJ} \tag{10}$$

at the main stage of compression, the duration of which is $t_{\rm main} \approx 10$ ns and radiation temperature is $T_{\rm R}^{\rm main} \approx 300$ eV [39, 48, 50, 54, 60, 67].

We calculate the energy of the equilibrium thermal radiation $E_{\rm w}$ that is absorbed by a gold wall with an area $A_{\rm w}$ at a radiation temperature $T_{\rm R}$, which does not change during a time interval τ, using the formula [54]

$$\frac{E_{\rm w}}{A_{\rm w}}\,[\text{MJ cm}^{-2}] \approx 5.2\times 10^{-3}\left(\frac{T_{\rm R}}{100\text{ eV}}\right)^{3.3}\left(\frac{\tau}{1\text{ ns}}\right)^{0.62}. \tag{11}$$

The area $A_{\rm w}$ primarily consists of the walls of the secondary hohlraum $A_{\rm w}^{\rm sh}$; it also includes the surface of the gold or gold-plated additional structural elements intended to improve the symmetry of the compression of the secondary fuel capsule and/or other purposes (for example, implementing fast ignition) [29, 31, 52, 61]. We let $E_{\rm w}^{\rm main}$ denote the value of $E_{\rm w}$ that corresponds to the main compression stage. Substituting $\tau = t_{\rm main}$ and $T_{\rm R} = T_{\rm R}^{\rm main}$ in Eqn (11) yields $E_{\rm w}^{\rm main}/A_{\rm w} \approx 814$ kJ cm^{-2}.

In estimating the permissible dimensions of the secondary hohlraum, we assume that its main part is a cylindrical pipe whose ends are closed with semispherical lids; the ratio of the pipe length to its inner radius $r_{\rm i}$ is 3 (this requirement is set to ensure sufficiently unhindered diffusion of thermal radiation [50]; see also [76, 77]); the centers of the fuel capsules coincide with the centers of the pipe bases (see the Figure),

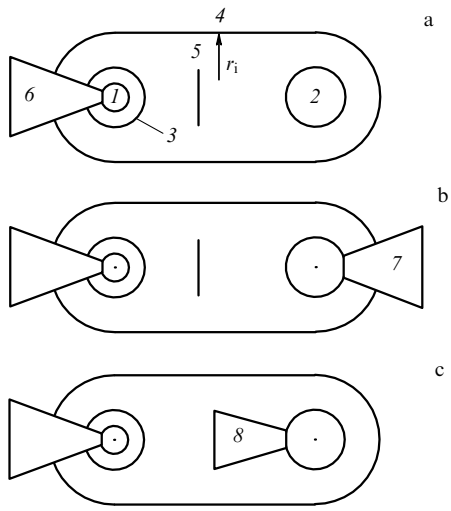

Figure. Targets for initiating a microexplosion with compression of fuel with a small value of $x_{\rm T}^{\rm main}$ using thermal radiation from a DT microexplosion. *1* is the capsule containing a DT fuel; *2* is the secondary fuel capsule; *3* is the primary hohlraum; *4* is the secondary hohlraum; *5* is the protective screen; and *6–8* are fast ignition cones.

$$E_{\rm c} + E_{\rm w}^{\rm main} + \rho_{\rm th} V^{\rm sh} \approx 0.7\,\eta_{\rm rad}^{\rm DT}\,Y \approx 175 \text{ MJ}, \tag{12}$$

where $\rho_{\rm th} \approx 111$ kJ cm^{-2} is the volume density of the energy of thermal radiation with a temperature of 300 eV, and $V^{\rm sh}$ is the volume of the secondary hohlraum. The factor 0.7 in Eqn (12) is introduced to approximately take two effects into account: some photons are emitted after the main irradiation of the secondary fuel capsule has been completed and radiation leaks through holes in the walls of the secondary hohlraum [29, 31, 50, 61]. The holes can be used to input laser radiation with the aim to compress the DT fuel and/or improve the compression of the secondary fuel capsule [31, 48, 50, 54, 61–66]. The energy of the thermal radiation contained in relatively small hohlraums that are usually discussed in the literature (see, e.g., [54, 62–70, 73, 74]) can be ignored; however, the assumption that this energy is small in a large hohlraum must be verified, strictly speaking [29, 31, 61]. In the setup under consideration, $A_{\rm w}^{\rm sh} \approx 10\pi r_{\rm i}^2$ and $V^{\rm sh} \approx (13/3)\,\pi r_{\rm i}^3$. Using these formulas and Eqns (10) and (12), we conclude that for $A_{\rm w} = A_{\rm w}^{\rm sh}$, i.e., if the secondary hohlraum does not contain any additional structural elements, $r_{\rm i} \approx 2.45$ cm. We note that if the energy of the contained thermal radiation is not taken into account or, in other words, the third term in the left-hand side of Eqn (12) is omitted, we arrive at $r_{\rm i}(A_{\rm w} = A_{\rm w}^{\rm sh}) \approx 2.62$ cm. Below, we use the value [50]

$$r_{\rm i} = 2.3 \text{ cm}, \tag{13}$$

which corresponds, for example, to the presence in the secondary hohlraum of one or more gold or gold-plated structural elements whose total irradiated area is approximately 26 cm^2 (see the Figure, where the fast ignition cones [4, 31, 33, 48–50, 55, 68, 71–73, 78–80] and protective screens, whose purpose is explained in Section 4.2.2, are displayed).

We consider a setup where the ablator of the secondary fuel capsule primarily consists of a low-Z element or a

material consisting of more than one such element [29, 31, 47, 49, 50, 54, 60–67]. The rate of the absorption of equilibrium thermal radiation by the unit area of that ablator can be described by the formula $W_{\rm abl} = k_{\rm abl}\sigma T_{\rm R}^4$, where $k_{\rm abl}$ is a coefficient in the range 0.5–1.0 and σ is the Stefan–Boltzmann constant [54, 67]. Substituting the values $k_{\rm abl} = 0.5$ and $T_{\rm R} = T_{\rm R}^{\rm main}$ in this formula, we obtain $W_{\rm abl} \approx 4.16 \times 10^{14}$ W cm^{-2}. Assuming that condition (10) is virtually completely satisfied at the main compression stage, we obtain approximately 4.8 cm^2 as the average ablator surface at this stage. We let $r_{\rm eff}$ denote the radius of a sphere with that surface area. The initial radius of the secondary fuel capsule $R_{\rm c}$ must apparently be greater than $r_{\rm eff} \approx 0.62$ cm. Nevertheless, the excess of $R_{\rm c}$ over $r_{\rm eff}$ is not large, and the upper bound for $R_{\rm c}$ is approximately 1 cm, a value that is compatible with condition (13) and seems to be sufficient for essentially unimpeded propagation of thermal radiation into the secondary hohlraum area shown in the picture to the right of the secondary fuel capsule. Thus, in an example considered in [45], the energy $E_{\rm comp}^{\rm fuel}$ of the compressed fuel with $m_{\rm fuel} = 20$ mg is 1.15 MJ (this value is referred to in [45] as the 'initial internal energy'; the estimated energy release due to the microexplosion is 1.33 GJ). To attain this value of $E_{\rm comp}^{\rm fuel}$, it is sufficient to ensure the maximum implosion velocity $v_{\rm imp}^{\rm max} \approx \sqrt{2E_{\rm comp}/m_{\rm fuel}} \approx 3.4\times10^7$ cm s^{-1} (it is assumed here that the fuel heats up only insignificantly prior to attaining that velocity; see also [3, 4]). Setting the value $r_{\rm eff} + v_{\rm imp}^{\rm max} t_{\rm main}$ as the upper bound for $R_{\rm c}$, we obtain $R_{\rm c} \leqslant 0.96$ cm.

Of significant interest may also be scenarios with $E_{\rm c} < 20$ MJ and hence smaller $R_{\rm c}$. According to [54], the efficiency of indirect compression of the fuel capsule, i.e., the ratio $E_{\rm comp}^{\rm fuel}/E_{\rm c}$, can be as large as 0.15–0.20. Thus, the example in [45] quoted above can correspond to $E_{\rm c} \approx 5.8-7.7$ MJ.

According to [60], a DT microexplosion with $Y \approx 1$ GJ can be initiated in a hohlraum whose wall is a sphere with the outer radius $R_{\rm hw}^{\rm DT} \approx 1$ cm; as follows from Eqn (13), this is an indication that a hohlraum like this can be placed inside a secondary one [50]. This possibility obviously also persists when the actual value of $R_{\rm hw}^{\rm DT}$ is several dozen percent larger than the value reported in [60].

We show that the thermal radiation filling the secondary hohlraum can be emitted sufficiently rapidly. We assume that as a result of a DT microexplosion, the primary hohlraum instantly transforms at $t = 0$ into a plasma cloud, which can be considered a black body with a constant effective radius $R_{\rm bb} \approx 1$ cm and a temperature $T_{\rm bb}$ that linearly decreases during a time interval $t_{\rm main}$ from the initial value $T_{\rm bb1}$ to $T_{\rm bb2} \geqslant T_{\rm R}^{\rm main}$. In the simplest case, $R_{\rm bb}$ is approximately equal to $R_{\rm hw}^{\rm DT}$ [29, 31, 50, 61]. It can be shown that situations are possible where variation of $R_{\rm bb}$ during the time interval $0 \leqslant t \leqslant t_{\rm main}$ is small compared to $R_{\rm hw}^{\rm DT}$ or at least $r_{\rm i}$. In any event, if $R_{\rm bb}$ increases with time to at least $r_{\rm i}$, it is a factor that speeds up emission of thermal radiation.

Thus, the approximation we use corresponds to a conservative model. We let $E_{\rm bb}^{\rm eff}$ denote the difference between the thermal radiation energy emitted and absorbed by a black body under consideration during the time interval $0 \leqslant t \leqslant t_{\rm main}$. We then set $E_{\rm bb}^{\rm eff} = 175$ MJ [see (12)]. Using the formula

$$E_{\rm bb}^{\rm eff} \approx 4\pi\sigma R_{\rm bb}^2 \left[\int_0^{t_{\rm main}} T_{\rm bb}^4(t)\,{\rm d}t - (T_{\rm R}^{\rm main})^4 t_{\rm main} \right],$$

we obtain, for example, $T_{\rm bb1}(T_{\rm bb2} = 350\ {\rm eV}) \approx 415$ eV, $T_{\rm bb1}(T_{\rm bb2} = 300\ {\rm eV}) \approx 452$ eV. Such values of $T_{\rm bb1}$ are quite feasible (see above and also [10]).

4.2.2 Some methods for improving the symmetry and time profiling of compression of the secondary fuel capsule. Direct irradiation of the secondary fuel capsule by thermal radiation of the primary hohlraum heated with a DT microexplosion is undesirable or even impermissible because it degrades the compression symmetry [29, 31]. Such irradiation can be removed, for example, using a protective screen (see Figures a and b). Similar screens have been proposed previously for fusion targets where thermal radiation is generated by heavy ions [54, 70, 81].

For the target shown in Figure c, cone *8* is used as a protective screen. It is also intended for the fast ignition of the microexplosion of the secondary fuel capsule with a DT microexplosion. The seed of the secondary fuel capsule can be directly heated be means of an auxiliary microexplosion that occurs as a result of compression of the equimolar DT fuel in the cone (see [39, 71, 78–80]). Of interest is also the possible use of such a cone to implement other scenarios of fast ignition, including a cumulative jet (see, e.g., [31, 33, 39, 61, 82–84]).

Other actions may be needed to improve the symmetry and time profiling of the compression of the secondary fuel capsule [29, 31, 61]. Some of them are also applicable to compressing a DT fuel capsule using a driver.

In the setup where cones are not used for fast ignition, the simplest and most efficient way to attain maximum values of ρr is to subject the spherically symmetric fuel capsule to uniform irradiation (see, e.g., [54, 66]). The content of the hohlraum walls can also be modulated along their depth to enhance the symmetry of capsule irradiation [54, 69]. To ensure the high symmetry of fuel compression in the setup with significantly nonuniform irradiation of the capsule, ablator parameters (its composition and/or thickness) can be modulated [54, 70, 85].

If the cone is used for fast ignition, the maximum values of ρr are attained if the effect of the cone on compression is compensated by the nonuniform irradiation of the capsule [49, 72] and/or modulation of the ablator parameters. The same refers to scenarios where a single fuel capsule is used together with two cones for fast ignition (see, e.g., [33, 84, 86]). These scenarios can be useful for initiating a DT microexplosion for the targets discussed above and in what follows (see [86]).

Another efficient technique consists in using one or more partition walls that fully or partly block the radiation propagation channel and/or a screen encasing the secondary fuel capsule [29, 31, 61, 87]. The initial heating of these structural elements by thermal X-ray radiation should increase their transparency to that radiation [29, 31, 61]. This can be ensured if a low-Z element or a substance consisting of more than one such element is used as the main material for the partition walls (see, e.g., [88]).

4.2.3 Heating of the secondary fuel capsule by neutrons. To assess the effect of neutrons from a DT microexplosion on the secondary fuel capsule, we assume that its Y is fully determined by reaction (2) and that the kinetic energy $E_{\rm n}$ of each neutron escaping from the thermonuclear plasma is 10 MeV [29]. The velocity of such a neutron is approximately 4.4×10^9 cm s^{-1}, and hence in the situation under considera-

tion the neutrons reach the secondary fuel capsule. We consider the interaction of neutrons with deuterons and protons [29]. These processes are of interest because deuterium is the primary or, if used in a mixture with ^{3}He, one of the primary components of the fuel in the secondary capsule, while the light hydrogen isotope can be a component of the plastic ablator (see, e.g., [64–66, 70]).

In accordance with the assumptions made, the probabilities p_{Dn} and p_{pn} that a deuteron or a proton collides with a DT microexplosion neutron are given by the formulas

$$p_{\mathrm{Dn}} \approx \frac{\sigma_{\mathrm{nD}}(E_{\mathrm{n}} = 10\ \mathrm{MeV})\, N_{\mathrm{n}}}{36\pi r_{\mathrm{i}}^2}\,, \tag{14}$$

$$p_{\mathrm{pn}} \approx \frac{\sigma_{\mathrm{np}}(E_{\mathrm{n}} = 10\ \mathrm{MeV})\, N_{\mathrm{n}}}{36\pi r_{\mathrm{i}}^2}\,, \tag{15}$$

where σ_{nD} and σ_{np} are the effective cross section of neutron scattering on the deuteron and proton and $N_{\mathrm{n}} \approx 3.55 \times 10^{20}$ is the number of neutrons produced as a result of the DT microexplosion [see (9) and the Figure]. It is assumed here that the neutrons are not actually scattered in the region between the microexplosion and the deuterons and protons under consideration; this assumption corresponds to a negligibly small scattering of those neutrons by the thin protective screens shown in Figures a and b and cone *8* shown in Figure c.

We let $\langle E_{\mathrm{D}} \rangle$ and $\langle E_{\mathrm{p}} \rangle$ respectively denote the average kinetic energies acquired by the deuteron and proton as a result of a collision with a neutron. For $E_{\mathrm{n}} = 10$ MeV, the scattering of a neutron on a proton is isotropic in the center-of-mass frame and $\langle E_{\mathrm{p}} \rangle = 0.5 E_{\mathrm{n}} = 5$ MeV [89]. The scattering of such a neutron on a deuteron is a more complicated process because it is not isotropic in the center-of-mass frame, and $\sigma_{\mathrm{nD}}(E_{\mathrm{n}} = 10\ \mathrm{MeV})$ also contains a contribution of deuteron splitting, approximately equal to 0.1 b [89]. However, these details are not of significant importance for the analysis of the data presented here. In the approximation where the scattering of a neutron on a deuteron is an elastic process and is isotropic in the center-of-mass frame, $\langle E_{\mathrm{D}} \rangle (E_{\mathrm{n}} = 10\ \mathrm{MeV}) \approx 4.4$ MeV [89]. Using the values of N_{n}, $\langle E_{\mathrm{D}} \rangle$ and $\langle E_{\mathrm{p}} \rangle$ quoted above, $\sigma_{\mathrm{nD}}(E_{\mathrm{n}} = 10\ \mathrm{MeV}) \approx 1$ b, and $\sigma_{\mathrm{np}}(E_{\mathrm{n}} = 10\ \mathrm{MeV}) \approx 0.87$ b [89] and Eqns (13)–(15), we obtain

$$p_{\mathrm{Dn}} \langle E_{\mathrm{D}} \rangle \approx p_{\mathrm{pn}} \langle E_{\mathrm{p}} \rangle \approx 2.6\ \mathrm{eV}\,. \tag{16}$$

According to [90], if DT microexplosions are initiated without using the fast ignition regime, the permissible preheating of the fuel is 10^5 J g^{-1}, which approximately corresponds to 2.6 eV per atom. In a later study [54], this value was assumed to be $(1-5) \times 10^5$ J g^{-1}, i.e., approximately 2.6–13.0 eV per atom. Similar preliminary heating seems to also be permissible for fuel with a small value of $\langle x_{\mathrm{T}}^{\mathrm{main}} \rangle$, in any event, if the seed is used and a hot spot is created in the fast ignition mode (Figs b and c). Estimate (16) and similar estimates for the interaction of neutrons with nuclei of other light elements that can be contained in the ablator material, and with the ^{3}He nucleus show that requirements (9) and (13) correspond to preheating of fuel in the secondary capsules by neutrons being permissible even if the characteristic efficiency η_{trans} of the transfer to the fuel of the kinetic energy acquired by the deuteron and other nuclei as a result of collisions with neutrons is close to unity. The value of η_{trans} for deuterons and protons is several times smaller in many situations. It follows, for example, from the Bethe–Bloch formula in [35] that the stopping power S_{D} of a deuteron for a deuteron with the kinetic energy of the order of 1 MeV is approximately half of the stopping power of the light hydrogen isotope S_{h} for a proton with the kinetic energy $E_{\mathrm{d}}/2$. Using this fact and the tabular data for S_{h} from [91], for example, we obtain $S_{\mathrm{D}}(E_{\mathrm{d}} = 4.4\ \mathrm{MeV}) \approx 180$ MeV cm^2 g^{-1}. If the fuel consists of almost pure deuterium and has the shape of a spherical layer with an outer radius of 1 cm and mass of 20 mg prior to compression (see above and also [45]), the surface density of that layer is $\sigma_{\mathrm{fuel}} \approx 1.6 \times 10^{-3}$ g cm^{-2}, corresponding to

$$S_{\mathrm{D}}(E_{\mathrm{d}} = 4.4\ \mathrm{MeV})\, \sigma_{\mathrm{fuel}} \approx 0.29\ \mathrm{MeV}\,. \tag{17}$$

To accurately determine the values of η_{trans} for deuterons, protons, and heavier nuclei, more detailed calculations are apparently needed; however, example (17) already shows that η_{trans} for deuterons can be much less than unity. A similar result has been obtained for protons [29]. We emphasize that the estimated values of $p_{\mathrm{Dn}} \langle E_{\mathrm{D}} \rangle$ and similar parameters are weakly sensitive to the choice of E_{n}: if E_{n} increases, on the one hand, the kinetic energy transferred by the neutron to the deuteron or another nucleus increases, but, on the other hand, the cross section of neutron scattering on that nucleus decreases (see, e.g. [89]).

If required, the heating of the secondary fuel capsule by DT microexplosion neutrons with a fixed Y can be reduced, first of all by increasing the distance between fuel capsules [3, 4, 29, 50]. The energy absorption per unit area of some materials, for example, the equimolar alloy of gold and gadolinium, is approximately 20% less than that of gold [69, 74], which allows increasing the hohlraum dimensions [50]. The distance between fuel capsules can also be increased by optimizing the shape of the secondary hohlraum and, possibly, decreasing $T_{\mathrm{R}}^{\mathrm{main}}$ [see (11, 12)]. In targets whose design is similar to that shown in Figs a an b, an elongated neutron-scattering screen can be installed between fuel capsules [29]. If the main part of that screen consists of one or more light elements, then, to reduce the absorption of thermal radiation, its outer layer must consist of one or more heavy elements [29].

DT microexplosion neutrons can positively affect the symmetry of compression of the secondary fuel capsule at the initial stage of that process [31]. This is related to the possible insertion of fissionable elements into specific areas of its ablator and hence additional heating of those areas by fission fragments [31]. However, the efficacy of such techniques in power generation requires focused examination.

4.3 Breeding of tritium and the use of sodium and other materials for increasing heat release

In many studies that analyze options for using reactions (3), (4), and (6) for power generation, conditions are explored under which the escape of a small part of secondary tritium from the fusion reaction region would be sufficient for producing new fusion targets or, in other words, for sustaining power facility operations without breeding tritium in the reaction

$$^6\mathrm{Li} + \mathrm{n} \rightarrow \alpha + \mathrm{T} + 4.8\ \mathrm{MeV} \tag{18}$$

or any neutron breeding reaction [41–43, 45]. If a fuel with a small or zero value of $\langle x_{\mathrm{T}}^{\mathrm{main}} \rangle$ is compressed by thermal radiation from DT microexplosions or using that radiation,

and the energy release E_g of the series of microexplosions occurring as a result of the effect of a single target is rather moderate (of the order of 1–10 GJ), using reaction (18) most probably cannot be avoided. However, the amount of tritium produced in that way is several dozen percent smaller than that produced by a fusion plant of the same power W_{fus} where DT microexplosions or magnetic confinement of equimolar deuterium–tritium plasma are used. We note that a scenario was proposed in [42] to initiate the burning of deuterium with a DT microexplosion that does not involve reaction (18); however, the estimated minimum value of E_g needed for that scenario is not reported. It can be very large, of the order of 100 GJ or more (see [3, 4, 42]).

The neutrons not used for breeding tritium can be used to enhance the thermal power W_{th} of a power generation plant employing the reactions that accompany the capture of neutrons by ^{23}Na nuclei (see [34] and Section 2) or another element, for example, tin [92]. This approach is also applicable, albeit with lower efficiency, at power generation plants where DT microexplosions are used (its applicability is a more complicated issue if magnetic plasma containment is used). For example, study [92] presents projects of power generation plants where DT microexplosions are used and tritium is bred using reactions (18) and

$$^{7}\mathrm{Li} + \mathrm{n} \rightarrow \alpha + \mathrm{T} + \mathrm{n} - 2.5\ \mathrm{MeV}\,. \tag{19}$$

At a power generation plant of this kind, the tritium breeding ratio k_T, i.e., the ratio of the mass of the produced tritium to the mass of the consumed tritium, can be as high as approximately 1.4 [92]. The k_T values this high can probably be useful at an early stage of the development of fusion power generation industry when the tritium produced by one power generation plant is used to launch other plants [92]. For the full-fledged fission power generation industry, the authors of [92] choose the value $k_T = 1.05$, which is sufficient for compensating the decay and minor losses of tritium. To decrease k_T and increase the W_{th}/W_{fus} ratio, it is proposed to substitute part of the lithium with tin (both lithium and tin must be in a molten state); the ratio W_{th}/W_{fus} is then approximately 1.2 [29]. The value of W_{th}/W_{fus} in the version where tin is not used is not reported; however, based on the example presented in [44], we expect it to fall in the range 1.0–1.15.

The possibility to significantly increase W_{th}/W_{fus} if part of the lithium is substituted with sodium follows from the observation that E^{n}_{Na-Mg} is approximately 2.6 times larger than the energy release in reaction (18) and approximately 1.8 times larger than the energy release in the process that consists of reaction (19) and the subsequent participation of two neutrons in reaction (18). A comparison of the efficiency of using sodium and other elements is beyond the scope of this review.

The maximum increase in the ratio W_{th}/W_{fus} that can be attained using the technique under discussion is apparently dependent to a significant extent on the energy release of fusion reactions E^{n}_{fus}, which corresponds to the escape of a single neutron from the reaction region. If a fuel with a small or zero value of $\langle x_T^{main}\rangle$ is compressed by radiation from DT microexplosions or using that radiation, E^{n}_{fus} is strongly dependent on both the relative contribution of one or more DT microexplosions to E_g and the fuel burning scenario. In particular, an increase in the degree of burning out of 'secondary' ^{3}He results in a decrease in E^{n}_{fus} [see also (2)–(4) and (6)–(8)].

5. Some problems related to using the neutronless p – ^{11}B reaction

5.1 Environmental purity of the reactions and unacceptably high energy release in the case of inertial confinement with moderate fuel compression

Neutronless reaction (5), which can be regarded as both a thermonuclear fusion reaction and a thermonuclear spallation [10] or fission [40] reaction, is accompanied by several other reactions, including [9, 16, 17, 22]

$$\alpha + {}^{11}\mathrm{B} \rightarrow \mathrm{n} + {}^{14}\mathrm{N} + 0.2\ \mathrm{MeV}\,, \tag{20}$$

$$\mathrm{p} + {}^{11}\mathrm{B} \rightarrow \mathrm{n} + {}^{11}\mathrm{C} - 2.8\ \mathrm{MeV}\,.$$

Some boron hydrides are very toxic [93]. Therefore, a comprehensive analysis of the safe use of reaction (5) must include the analysis of the possible production of those hydrides in both normal and emergency situations. Nevertheless, electric power generation using reaction (5), if it is feasible, would be relatively 'cleaner' from the perspective of generating both radioactive and toxic substances (this reaction was assessed in [3, 4] as "environmentally cleaner than a chemical reaction"). Owing to this circumstance, methods to implement reaction (5) in practice are being sought very actively (see, e.g., [3, 4, 9–22, 27, 28, 47, 94–97]).

The main problems related to using reaction (5) for power generation arise from the smallness of its effective cross section σ_5 even at relatively high center-of-mass energy ε_{cm} of the collision of a proton and a ^{11}B nucleus [2–4, 9–20, 94–97]. This has a consequence that the temperature T_{ign5} at which this reaction ignites is high. The value of T_{ign5} varies depending on the analysis in which it is determined. For example, according to book [10], this temperature is 400 keV, while studies [13, 14] report a value of 87 keV. The temperatures approximately corresponding to the latter version of requirements can be attained even without using reaction (2) [13, 14]. If this reaction or, when necessary, other reactions are used to that end, the former version of the requirements can also be satisfied (see also [9, 28, 41, 47, 94]).

In generating electric power using inertial plasma confinement, the most important problem related to the smallness of σ_5 is that reaction (5) can only be efficient if the values of ρr are sufficiently large. For example, it is stated in book [10] that for igniting this reaction ρr must be approximately 50 g cm^{-2}, while the optimal value of ρr is approximately 500 g cm^{-2}. If fuel is compressed by microexplosions or using the microexplosions, ρr values this high seem to be attainable at a facility with one or more drivers with reasonable parameters (see also [3, 4, 27, 28]). However, at least as $\rho r \rightarrow 500$ g cm^{-2}, the bounds on the attainable values of ρ would most probably result (in the case of approximately spherically symmetric compression of fuel) in very large values of r and hence of m_{fuel}, which can be described by the formula

$$m_{fuel} \approx \frac{4\pi}{3}\,\frac{(\rho r)^3}{\rho^2}\,, \tag{21}$$

and therefore Y would be so large that reaction (5) can no longer be considered a powerful microexplosion. In today's situation, this would not be acceptable primarily for political reasons. The reasons why it is much easier to compress fuel for reaction (5) than to compress a deuterium–tritium mixture

and pure deuterium are not known. Equation (21) shows, for example, that for a fixed density ρ, in passing from the values $\rho r \approx 10-20$ g cm^{-2} sufficient for the efficient use of reactions (3), (4), and (6) to $\rho r \approx 500$ g cm^{-2}, the value of m_{fuel} increases by approximately a factor of $1.56 \times 10^4 - 1.25 \times 10^5$. Even if the relatively low ratio of the energy release in reaction (5) to the mass of the nuclei participating in that reaction, and, probably, the lower efficiency of fuel burnout in that reaction are taken into account, such a large increase in m_{fuel} would result in an increase in Y by a factor of no less than several hundred to several thousand.

We next consider an example of a proposal that is not feasible because of very high requirements for r and hence for m_{fuel}. It was proposed in [13, 14] to use reaction (5) to generate electric power by heating fuel with picosecond petawatt laser pulses and without compressing that fuel. The unfeasibility of such scenarios for electric power generation due to a very high value of Y for the efficient occurrence of that reaction can be traced to the requirements for ρr from [10] quoted above (in the setup under consideration, the characteristic density and radius of the fuel apparently correspond to the initial conditions rather than to the maximum compression stage). Evidence that this scenario is not feasible, which is based on a direct estimate of the characteristic rates of reaction (5) and plasma spread velocity, is reported in [39]. It was assumed that the plasma temperature is $T_{\text{ign5}} = 87$ keV [13, 14]; the initial concentration of boron nuclei is close to the concentration of atoms in solid boron, i.e., approximately 1.3×10^{23} cm^{-3} [98], and the cooling of the fuel and its heating by α particles are mutually compensated. According to this estimate, reaction (5) involves a significant fraction of the fuel only if its initial size in any direction is no less than 1 m [39], which is not acceptable: we then have $\rho r \approx 130$ g cm^{-2}. The initial dimensions of the fuel an order of magnitude smaller, which correspond, for example, to $\rho r \approx 13$ g cm^{-2}, are obviously unacceptable as well.

Preprint [9] contains a discussion of how reaction (5) can be used in blasting microexplosions where fuel is compressed to $\rho \sim 10^5$ g cm^{-3}. A compression this strong would result in acceptable values of m_{fuel} [see (21)] and Y even with $\rho r \approx 500$ g cm^{-2}; however, the feasibility of this scenario is currently far from obvious.

The feasibility of combining efficient initiation of reaction (5) with an acceptably low value of Y in the scenario proposed in [22], where both plasma compression and the generation of a strong magnetic field with laser radiation are used, is not clear either. It was argued in [22] that "initiation of the wave of burning with the specific features of the problem taken into account is a matter of separate study."

The very large pulsed energy release in the case of inertial plasma confinement and an insufficiently large value of ρ is also of paramount importance for reaction (1) and some other neutronless reactions [3, 4].

5.2 Radiation losses of optically thin plasma, resonances in the effective cross section of the p–^{11}B reaction, and chain reactions

Another conceptual problem arising from the smallness of the effective cross section σ_5 in reaction (5) is manifested if the optical thickness is sufficiently small for bremsstrahlung radiation [9, 94, 95]. If this is the case and if the temperatures of electrons T_e and ions T_i are the same, the energy losses due to bremsstrahlung radiation exceed the energy output in reaction (5) [9, 53, 94, 95]. If $T_e = T_i$, this problem is of no significance only for inertial confinement with strong compression [3, 4, 9]. Several approaches have been proposed to resolve the problem by creating a plasma with $T_e < T_i$ [9, 94]. It was also proposed to create a plasma with relatively low T_e and a nonthermal distribution of the energy of some protons [12, 97]. The energy losses due to bremsstrahlung radiation can be reduced further if a fuel with an increased content of hydrogen is used; for example, a fuel whose composition is $^{11}BH_5$ was considered in [9] as the optimal solution.

If ions are confined using an electrostatic mechanism (see, e.g., [15, 21, 95]), additional mechanisms of energy losses are in effect [95]. The data reported in [95] suggest that if such a confinement mechanism is used, reaction (5) cannot yield an energy gain.

The dependence of σ_5 on the kinetic energy of collision ε_{cm} in the center-of-mass frame exhibits several resonances [9, 19, 96, 97]. Some studies explored the options to expediently use or at least clearly observe a resonance that corresponds to $\varepsilon_{\text{cm}} \approx 590$ keV (see, e.g., [9, 12, 18, 20, 97, 99–102]).

It was proposed in [12] and [97] to make reaction (5) occur in an asymmetric centrifugal trap, an open magnetic trap with a radial electric field (paper [12] was published simultaneously with a negative review of it [99] and a response [100] to that review). The proposed trap was supposed to confine fully ionized ^{11}B ions, electrons, and protons of two types: fast and slow [12, 97]. The energy distribution of boron ions, electrons, and slow protons in a rotating frame (RF) is considered to be the thermal distribution with a temperature of 55.6 keV, and the kinetic energy of fast protons in that frame is chosen to be 590 keV [12] or 550 keV [97].

One of the most important features that specifies the parameters of confined plasma is that the time $\tau_{1\text{P}}$ a fast proton spends in plasma is small, significantly smaller than the time during which it transfers its energy to electrons, and is determined by scattering on a boron ion at a large angle in the range $\pi/4 - \pi/3$ [12, 97]. In the quoted example, $\tau_{1\text{P}} = 0.61$ s, the concentration of boron ions is $n_{\text{B}} = 10^{13}$ cm^{-3}, the average product of σ_5 and the velocity of fast protons with respect to boron ions is 1.0×10^{-15} cm^3 s^{-1} [12] or 9.2×10^{-16} cm^3 s^{-1} [97]. With these parameters, the probability p_5 that a fast proton participates in reaction (5) during the time it stays in the trap is approximately $(5.6-6.1) \times 10^{-3}$. It is argued that according to experimental data, the design of the trap ensures efficient recuperation of the energy of charged particles and, primarily, protons [12, 97, 100] (the term "recuperation of the energy of particles decelerated in electric fields" is used). This recuperation should actually make small values of p_5 acceptable. The technique used for calculating $\tau_{1\text{P}}$ and, in particular, justification of the assumption of small energy losses of fast protons in their collisions with electrons is not expounded in [12, 97], as was noted in report [99] on [12].

In our opinion, the operability of a power generation plant with the trap proposed in [12, 97] requires further examination; first of all, the possibility of efficiently recuperating the energy of charged particles and a reliable calculation of $\tau_{1\text{P}}$ and p_5 for a plasma rotating in crossed fields have to be presented. We note that calculations of parameters similar to p_5 in the plasma not involved in rotational motion are reported in [9, 45, 101, 103, 104].

Possible manifestations of the resonance under discussion was explored in [9, 20, 101, 102] as a factor that causes development of a chain reaction; this last consists in the

acceleration of protons as a result of scattering on them of the α particles generated in reaction (5) and the subsequent participation of those protons in reaction (5).

According to [9], at a temperature of 150–350 keV and a concentration of $10^{16}-10^{26}$ cm^{-3}, this reaction, in combination with other 'nonthermal' effects, results in a 5% to 15% increase in the rate of reaction (5). The type of particles with the required concentration is not specified, but because the concentrations of all particles in the plasma under consideration are comparable, this issue is of no significant importance.

It was argued in [20] that this chain reaction is observed in experiments at the PALS laser facility (Prague Asterix Laser System). A silicon target also containing ^{11}B and hydrogen was irradiated in those experiments with a laser pulse whose energy was 500–600 J, to produce approximately 4×10^8 α particles [105, 106]. Only the α particles that moved in the direction of the irradiated surface escaped from the target, and hence the total number N_α of generated α particles is approximately twice as large [106]. The α particles were generated as a result of laser acceleration of approximately 10^{11} protons [106]. The value of N_α estimated without making the assumption of a chain reaction is $N_\alpha \approx 7 \times 10^8$, a result that agrees well with experimental data [106]. No critical comments on this estimate have been made either in [20] or in other publications. It was shown in [101] that the probability of a collision of an α particle with a proton in the PALS experiments that would result in accelerating that proton to an energy corresponding to a relatively large value of σ_5 is insufficient for a physically significant manifestation of the chain reaction. Regarding the resonance at $\varepsilon_{\rm cm} \approx 590$ keV, this result was rederived using quite a different model [102]. Plans were announced to study options for the development of a chain reaction owing to the presence of a narrow resonance at a proton energy of 163 keV [102].

It was argued in [18] that another chain reaction is observed in PALS experiments. Its mechanism is as follows. As a result of the scattering of the α particles generated in reaction (5) on ^{11}B nuclei, a significant number of the ^{11}B nuclei are accelerated to the kinetic energies $\varepsilon_{^{11}\rm B}$ close to 500 keV (it is assumed that the energy of each α particle is $\varepsilon_\alpha \approx 2.9$ MeV) [18]. Because σ_5 exhibits a resonance at $\varepsilon_{\rm cm} \approx 590$ keV, a conclusion is made that such ^{11}B nuclei participate in reaction (5) with a high probability [18]. This conclusion is apparently incorrect [104]: for a small kinetic energy of the proton $\varepsilon_{\rm cm} \approx 0.076\varepsilon_{^{11}\rm B}$, $\varepsilon_{\rm cm}(\varepsilon_{^{11}\rm B} \approx 500$ keV$) \approx$ 38 keV, and the cross section $\sigma_5(\varepsilon_{^{11}\rm B} \approx 500$ keV$)$ is small [90], and the production of α particles with initial kinetic energies over 2.9 MeV does not result in accelerating the ^{11}B nuclei to the values of $\varepsilon_{^{11}\rm B}$ that correspond to large σ_5.

It was suggested in [16, 17] to arrange a chain reaction involving reactions (5) and (20),

$$\alpha + {}^{11}\mathrm{B} \rightarrow \mathrm{p} + {}^{14}\mathrm{C} + 0.8\ \mathrm{MeV}\,, \tag{22}$$

$$\mathrm{n} + {}^{10}\mathrm{B} \rightarrow \alpha + {}^{8}\mathrm{Li} + 2.8\ \mathrm{MeV}\,, \tag{23}$$

by irradiating a sample consisting of ^{10}B and ^{11}B with protons (such a sample could be a natural mixture of boron isotopes). It was argued that initiating this reaction would allow overcoming the difficulties related to the practical use of reaction (5) [16, 17].

In making qualitative estimates intended to justify the feasibility of the chain reaction under discussion and find the conditions for that reaction to be efficient, it was assumed that each α particle produced in reaction (5) or (23) participates in reaction (20) or (22) [16, 17]. Thus, those estimates failed to take into account that, due to the α-particle deceleration in plasma and, to an even greater extent, in unionized matter, some α particles are decelerated without participating in the nuclear reactions (it was noted in [17] that deceleration of particles and other processes were not taken into account, and numerical simulation taking all those effects into account is needed). In matter with the electron temperature up to 100 keV, this part of α particles is dominant, and therefore the chain reaction under discussion would not make initiating reaction (5) a less challenging problem [104].

It has been argued recently that the actual values of σ_5 at $\varepsilon_{\rm cm}$ in a range of approximately 0.6 to 3.5 MeV are significantly larger than those published earlier [19]. For example, according to [9], the maximum value of σ_5 is approximately 1.4 b, while according to [96], it is about 1.2 b. The largest ratio of the 'new' and 'old' values of σ_5, which is about seven, corresponds to $\varepsilon_{\rm cm} \approx 3.4$ MeV [19]. If the 'new' σ_5 are confirmed, this may reverse the conclusions regarding the feasibility of different versions of reaction (5) discussed previously (see also [41]).

6. Problems related to the expediency of large-scale use of lunar ^{3}He in terrestrial power generation

The proposal that ^{3}He can be delivered from the Moon to Earth to be widely used as a component of fusion fuel for power generation on Earth (see, e.g., [11, 23–25, 43]) requires further examination.

Several problems related to that delivery have been analyzed in detail by Stott, who concluded that the project is inexpedient [8]. One of Stott's arguments is that the ^{3}He concentration on the lunar surface is so low that a ton of lunar rock contains less energy than a ton of coal [8].

We present quantitative data evidencing the relatively low 'specific energy capacity' of lunar rocks as a source of ^{3}He.

According to [25], "the average concentration of helium-3 in a surface layer 3 meters thick is about 10 milligrams per ton... and, in the areas of highly Ti-basalts, the lunar maria, it may be as high 20 milligrams per ton or more." It is easy to show that even if the entire ^{3}He contained in one kilogram of lunar rock participated in reaction (6), the energy release in that reaction would be on average approximately 5.9 MJ and, if lunar mare rock was used, approximately 12 MJ or more. For comparison, the specific calorific capacity of gasoline and oil is approximately 44 MJ kg^{-1}, and the calorific effect of A-grade anthracite coal is in the range 32–34 MJ kg^{-1}, if the losses related to evaporation of the water it contains are not taken into account and in the range 19–27 MJ kg^{-1} if those losses are accounted for [107].

The average specific energy capacity of lunar rocks to be used as a source of ^{3}He is three orders of magnitude smaller than the same parameter of sea water used as a source of deuterium. The accurate value of the ratio of those specific energy capacities depends on the concentration of deuterium in water, which varies to some extent with the geographical location of the water intake site [108] and the deuterium burnout balance (see (7), (8), and [34]).

We note that despite the small concentration of ^{3}He in lunar rocks, mining ^{3}He on the Moon may be advantageous from the energy perspective [24].

Large-scale mining of ^{3}He on the Moon that involves processing large amounts of lunar rock would result in

changing the natural state of significant areas of the lunar surface, which may be considered an environmental problem [8]. We note that some areas on the far side of the Moon are of significant interest as sites for the deployment of radio telescopes (see, e.g., [109]).

According to [8], in systems with magnetic plasma confinement, if the power of fusion energy release is fixed, a transition from using reaction (2) to reactions with an optimal mixture of D and ^{3}He (the approximate composition of that mixture is 70% D and 30% ^{3}He) would result in a decrease in the total neutron flux by a factor of only three. A comparison of scenarios with the compression of fuel with microexplosions or using microexplosions and various values of $\langle x_{^3\mathrm{He}}^{\mathrm{main}} \rangle$, including zero, has not been made. The generation of neutrons is apparently inevitable in all scenarios of this kind. Delivering ^{3}He from the Moon and its production on Earth [8, 33, 41–43, 45, 51–53] have not been compared, as was noted in study [43] published as early as 1989. Therefore, the expediency of the delivery of ^{3}He from the Moon to be used for large-scale power generation in accordance with scenarios with inertial plasma confinement needs dedicated examination.

The expediency of mining lunar ^{3}He on a limited scale, especially as a by-product of mining other substances (see also [23–25]), is of independent interest and requires a special study.

7. Conclusion

An optimal version of using reactions (3), (4), and (6) and inertial plasma confinement to generate electric power seems to initiate microexplosions with the fuel compressed to a small value of $\langle x_{\mathrm{T}}^{\mathrm{main}} \rangle$ either by the thermal radiation of one or more DT microexplosions or with the use of that radiation and one or more drivers. Reaction (6) then mainly involves the 'secondary' ^{3}He that is produced directly in the microexplosion plasma. The main prerequisite for implementing such scenarios is the availability of techniques for the efficient initiation of DT microexplosions with $Y \approx 1$ GJ.

Both the escape of some ^{3}He from plasma with physically significant reactions (3) and (4) and the decay of the tritium generated in operations of fusion power generation plants can presumably enable using ^{3}He as a fuel component for some power generation plants [8, 33, 41–43, 45, 51–53].

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