Electric Cumulative Thermonuclear Reactors

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Abstract

During past sixty years, scientists spent tens of billion US dollars attempting to develop useful thermonuclear energy. However, they cannot yet reach a sustained stable thermonuclear reaction. They still are promising publically, after another 15 – 20 years, and more tens of billions of US dollars to finally design the expensive workable industrial installation, which possibly will produce electric energy more expensive than current heat, wind and hydro-electric power generation stations can in 2016.

The author offers the new, small and cheap electric cumulative thermonuclear reactors, which increases the temperature and pressure of its nuclear fuel by millions of times, reaches the required ignition stage and, ultimately, a constant well-contained thermonuclear reaction. Electric Cumulative AB Reactors contain several innovations to achieve its power output product. Chief among them in electric thermonuclear reactors are using moving cumulative explosives and an electric discharge, which allows to accelerate the fuel and special nucleus to very high speed which (as shown by integral computations) compresses the fuel thousands times and heats the fuel by electric impulse to hundreds of millions degrees of temperature.

In electric cumulative version of AB thermonuclear reactors, the fuel nucleus are accelerated by high electric voltage (15 ÷ 60 kV) up the hundreds millions degree and cumulative compressed into center of the spherical fuel cartridge. The additional compressing and combustion time the fuel nucleus may have from heavy nucleus of the fuel cartridge. The main advantages of the offered method are very small fuel cartridge (11-18 mm) of the full reactor installation (reactor having spherical diameter (0.3 - 3 m), using the thermonuclear fuel at room-temperature and achieves the possibility of using the offered thermonuclear reactor for transportation (ships, trains, aircrafts, rockets, etc.). Author gives theory and estimations of the suggested reactors. Author also is discussing the problems of converting the received thermonuclear energy into mechanical (electrical) energy and into rocket thrust. Offered small micro-reactors may be used as heaves (propellant after ignition, fusee) for small artillery nuclear projectiles and bombs.

Keywords: *Micro-thermonuclear reactor, Cumulative electric thermonuclear reactor, Impulse thermonuclear reactor, transportation thermonuclear reactor, aerospace thermonuclear engine, nuclei fusee, thermonuclear rocket.*

INTRODUCTION

Brief Information about Thermonuclear Reactors

Fusion power is useful energy generated by nuclear fusion reactions. In this kind of reaction, two light atomic nuclei fuse together to form a heavier nucleus and release energy. The largest current nuclear fusion experiment, JET, has resulted in fusion power production somewhat larger than the power put into the plasma, maintained for a few seconds. In June 2005, the construction of the experimental reactor ITER, designed to produce several times more fusion power than the power into it generating the plasma over many minutes, was announced. The unrealized production of net electrical power from fusion machines is planned for the next generation experiment after the still unsuccessful ITER.

Unfortunately, this task is not easy, as scientists thought early on. Fusion reactions require a very large amount of energy to initiate in order to overcome the so-called *Coulomb barrier* or *fusion barrier energy*. The key to practical fusion power is to select a fuel that requires the minimum amount of energy to start, that is, the lowest barrier energy. The best fuel from this standpoint is a one-to-one mix of deuterium and tritium (D –T); both are heavy isotopes of hydrogen. The D-T mix has suitable low barrier energy. In order to create the required conditions, the fuel must be heated to tens of millions of degrees, and/or compressed to immense pressures.

At present, D-T is used by two main methods of fusion: inertial confinement fusion (ICF) and magnetic confinement fusion (MCF)--for example, tokomak device.However, tritium is very expensive.

In inertial confinement fusion (ICF), nuclear fusion reactions are initiated by heating and compressing a target. The target is a pellet that most often contains D –T (often only micro or milligrams). Intense focused laser or ion beams are used for compression of pellets. The beams explosively detonate the outer material layers of the target pellet. That accelerates the underlying target layers inward, sending a shockwave into the center of each pellet's mass. If the shockwave is powerful enough, and if high enough density at the center is achieved, some of the fuel will be heated enough to cause pellet fusion reactions. In a target which has been heated and compressed to the point of thermonuclear ignition, energy can then heat surrounding fuel to cause it to fuse as well, potentially releasing tremendous amounts of energy.

Magnetic confinement fusion (MCF). Since plasmas are very good electrical conductors, magnetic fields can also be configured to safely confine fusion fuel. A variety of magnetic configurations can be used, the basic distinction being between magnetic mirror confinement and toroidal confinement, especially tokomaks and stellarators.

Lawson criterion. In nuclear fusion research, the Lawson criterion, first derived by John David Lawson (1923-2008) in 1957, is an important general measure of a system that defines the conditions needed for a nuclear fusion reactor to reach *ignition* stage, that is, the heating of the plasma by the products of the fusion reactions is sufficient to maintain the temperature of the plasma against all losses without external power input. As originally formulated the Lawson criterion gives a minimum required value for the product of the plasma (electron) density n_e and the "energy confinement time" τ. Later analyses suggested that a more useful figure of merit is the "triple product" of density, confinement time, and plasma temperature T. The triple product also has a minimum required value, and the name "Lawson criterion" often refers to this important inequality.

The key to practical fusion power is to select a fuel that requires the minimum amount of energy to start, that is, the lowest barrier energy. The best known fuel from this standpoint is a one-to-one mix of deuterium and tritium; both are heavy isotopes of hydrogen. The D-T mix has a low barrier.In order to create the required conditions, the fuel must be heated to tens of millions of degrees, and/or compressed to immense pressures. The temperature and pressure required for any particular fuel to fuse is known as the Lawson criterion. For the D-T reaction, the physical value is about

$$L = nT\tau > (10^{20} – 10^{21}) \text{ in CI units,}$$

Where T is temperature, [KeV], 1 eV = 1.16×10^4 K; n is matter density, [1/m^3]; τ is time, [s]. This equation is in metric system. The thermonuclear reaction of $^2H + {}^3D$ realizes if $L > 10^{20}$ in CI (meter, kilogram, second) units or $L > 10^{14}$ in 'cgs' (centimeter, gram, second) units.

This number has not yet been achieved in any fusion reactor, although the latest generations of fusion-making machines have come significantly close to doing so. For instance, the reactor TFTR has achieved the densities and energy lifetimes needed to achieve Lawson at the temperatures it can create, but it cannot create those temperatures at the same time. Future ITER aims to do both.

The Lawson criterion applies to inertial confinement fusion as well as to magnetic confinement fusion but is more usefully expressed in a different form.

Following the above derivation of the limit on $n_e\tau_E$, we see that the product of the density and the radius must be greater than a value related to the minimum of $T^{3/2}/\langle\sigma v\rangle$ (here σ is Boltzmann constant, v is ion speed). This condition is traditionally expressed in terms of the mass density $\rho$and R-radius of fuel pellet:

$$\rho R > 1 \text{ g/cm}^2 .$$

To satisfy this criterion at the density of solid D+T (0.2 g/cm^3) would require implausibly large laser pulse energy. Assuming the energy required scales with the mass of the fusion plasma ($E_{laser} \sim \rho R^3 \sim \rho^{-2}$), compressing the fuel to 10^3 or 10^4 times solid density would reduce the energy required by a factor of 10^6 or 10^8, bringing it into a realistic range. With a compression by 10^3, the compressed density will be 200 g/cm^3, and the compressed radius can be as small as 0.05 mm. The radius of the fuel before compression would be 0.5 mm. The initial pellet will be perhaps twice as large since most of the mass will be ablated during the compression stage by a symmetrical energy input bath.

The fusion power density is a good figure of merit to determine the optimum temperature for magnetic confinement, but for inertial confinement the fractional burn-up of the fuel is probably more useful. The burn-up should be proportional to the specific reaction rate ($n^2\langle\sigma v\rangle$) times the confinement time (which scales as $T^{1/2}$) divided by the particle density n: burn-up fraction ~ $n^2\langle\sigma v\rangle T^{-1/2} / n \sim (nT)\,(\langle\sigma v\rangle/T^{3/2})$

Thus the optimum temperature for inertial confinement fusion is that which maximizes $\langle\sigma v\rangle/T^{3/2}$, which is slightly higher than the optimum temperature for magnetic confinement.

*Short history of thermonuclear fusion.*One of the earliest (in the late 1970's and early 1980's) serious attempts at an ICF design was *Shiva*, a 20-armed neodymium laser system built at the Lawrence Livermore National Laboratory (LLNL) in California that started operation in 1978. Shiva was a "proof of concept" design, followed by the *NOVA* design with 10 times the power. Funding for fusion research was severely constrained in the 80's, but NOVA nevertheless successfully gathered enough information for a next generation machine whose goal was ignition. Although net energy can be released even without ignition (the breakeven point), ignition is considered necessary for a *practical* power system.

The resulting design, now known as the National Ignition Facility (NIF), commenced being constructed at LLNL in 1997. Originally intended to start construction in the early 1990s, the NIF is now six years behind schedule and over-budget by some $3.5 billion. Nevertheless many of the problems appear to be due to the "Big Science Laboratory" mentality and shifting the focus from pure ICF research to the nuclear stewardship program, LLNLs traditional nuclear weapons-making role. NIF "burned" in 2010, when the remaining lasers in the 192-beam array were finally installed. Like those earlier experiments, however, NIF has failed to reach ignition and is, as of 2016, generating only about 1/3rd of the required energy levels needed to reach full fusion stage of operation.

Laser physicists in Europe have put forward plans to build a £500m facility, called HiPER, to study a new approach to laser fusion. A panel of scientists from seven European Union countries believes that a "fast ignition" laser facility could make a significant contribution to fusion research, as well as supporting experiments in other areas of physics. The facility would be designed to achieve high-energy gains, providing the critical intermediate step between ignition and a demonstration reactor. It would consist of a long-pulse laser with energy of 200 kJ to compress the fuel and a short-pulse laser with energy of 70 kJ to heat it.Confinement refers to all the conditions necessary to keep plasma dense and hot long enough to undergo fusion:

- *Equilibrium:* There must be no net forces on any part of the plasma, otherwise it will rapidly disassemble. The exception, of course, is inertial confinement, where the relevant physics must occur faster than the disassembly time.
- *Stability:* The plasma must be so constructed that small deviations are restored to the initial state, otherwise some unavoidable disturbance will occur and grow exponentially until the plasma is destroyed.
- *Transport:* The loss of particles and heat in all channels must be sufficiently slow. The word "confinement" is often used in the restricted sense of "energy confinement".

To produce self-sustaining fusion, the energy released by the reaction (or at least a fraction of it) must be used to heat new reactant nuclei and keep them hot long enough that they also undergo fusion reactions. Retaining the heat generated is called energy *confinement* and may be accomplished in a number of ways.

Hydrogen bomb weapons require no confinement at all. The fuel is simply allowed to fly apart, but it takes a certain length of time to do this, and during this time fusion can occur. This approach is called *inertial confinement*. If more than about a milligram of fuel is used, the explosion would destroy the machine, so controlled thermonuclear fusion using inertial confinement causes tiny pellets of fuel to explode several times a second. To induce the explosion, the pellet must be compressed to about 30 times solid density with energetic beams. If the beams are focused directly on the pellet, it is called *direct drive*, which can in principle be very efficient, but in practice it is difficult to obtain the needed uniformity. An alternative approach is *indirect drive*, in which the beams heat a shell, and the shell radiates x-rays, which then implode the pellet. The beams are commonly laser beams, but heavy and light ion beams and electron beams have all been investigated and tried to one degree or another.

Data of some current inertial laser installations:

1. NOVA uses laser NIF (USA), has 192 beams, impulse energy up 120 kJ. One reach density 20 g/cm^3, speed of cover is up 300 km/s.
   NIF has failed to reach ignition and is, asof 2013, generating about 1/3rd of the required energy levels. NIF cost is about $3.5B.
2. YiPER (EU) has impulse energy up 70 kJ.
2. OMEGA (USA) has impulse energy up 60 kJ.
3. Gekko-XII (Japon) has impulse energy up 20 kJ. One reaches density 120 g/cm^3.
4. Febus (France) has impulse energy up 20 kJ.
5. Iskra-5 (Russia) has impulse energy up 30 kJ.

In given research author offers the new cheap thermonuclear reactors and fuses for nuclear projectiles. In early this method was described in [1] – [4]. Below are cheaper and simpler reactors.

Description and Innovations of Electric Cumulative AB reactors

Description.

Laser method. Disadvantages.

Thermonuclear reactors and, in particular, Laser methods are have been under development for about 60 years. Governments have already spent tens billions of US dollars, but it is not yet seen as an industrial application of thermonuclear energy for the coming 10-15 years. The laser has very low efficiency (3- 3%), high-pressure acts every shot time (10^{-9}– 10^{-10} s), enough energy not delivered to the center of the spherical fuel pellet (low temperature), there are many future problems the radioactivity and converting the thermonuclear energy into useful energy.

Cumulative method. Early author offered four the new methods (reflex, cumulative, impulse, ultra-cold)[1 – 4], which is cheaper by thousands of times, more efficiency and does not have many disadvantages of the laser and magnetic methods. In given article the author offers three versionsof the electric cumulative improved reactors. Detailed consideration of advantages the new methods and computation proofs are in next paragraph.

Outline of the new electric cumulative reactors and method.

The improved version 1 of the electric AB thermonuclear reactors are presented in figures 1 – 3.

The new thermonuclear reactor contains: small (spherical diameter is 11 – 18 mm) thermonuclear cartridge (special fuel ampule, granule, beat, pellet, Fig.1), thermonuclear reactor (sphere diameter is 0.3 – 3 m. Fig.2). Reactor has two Version 1 - 2. In Version 1the reactor has the additional installations for converting the nuclear energy into an electric, mechanical energy, in Version 2 the reactor converts the thermonuclear energy in a rocket thrust (fig. 3).

The fuel cartridge has (fig.1): the spherical shell 1; conductive layer 2 connected to condenser 7; layer 3 of heavy material (molar mass about 200), (option); layer 4 contains the thermonuclear fuel in a solid compound (option): internal volume of cartridge 5; edge 6 of a conductive needle connected with charged condenser 7, or very small conductive compressed fuel pellet (option); electric capacitor 7 connected to the layer 2, the edge needle 6 and source of energy.

The cartridge has three versions:

1) The Version 1 contains the layers 3-4 and vacuum 5.
2) The Version 2 not contains the layers 3-4 (or has only 3), but contains the gas thermonuclear fuel in volume 5 (in room temperature); 6 – edge of a conductive needle connected with charged condenser 7.

3) Version 3 is version 1 – 2, but one has the additional very small pellet in center of cartridge. Pellet has a thin conductive layer over thin cover and compressed fuel into pellet located on needle edge (Fig.1).

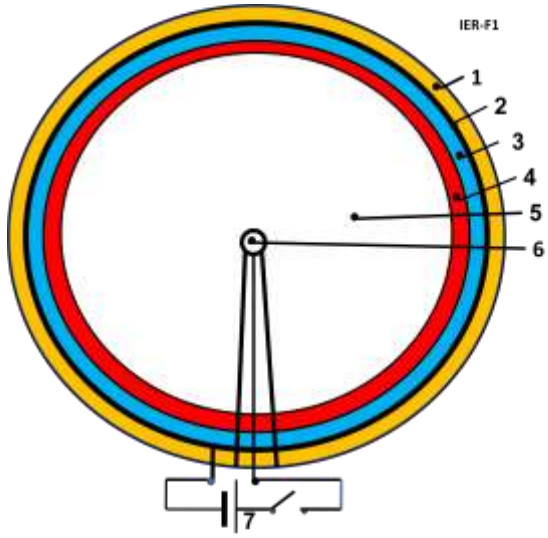


Fig.1. Cartridge (special fuel ampule, pellet) of the thermonuclear fuel, sphere of diameter 1÷ 2 cm. *Notations:* 1 – spherical shell of fuel cartridge; 2 – conductive layer connected to condenser 7; 3 - layer of heavy material (molar mass about 200), (option); 4 – layer contains the thermonuclear fuel in a solid compound (option);
Cartridge has three versions:
1) The Version 1 contains the layers 3-4 and vacuum 5.
2) The Version 2 not contains the layers 3-4, but contains the gas thermonuclear fuel in volume 5 (in room temperature); 6 – edge of a conductive needle connected with charged condenser 7.
3) Theversion 3 has very small compressed fuel pellet having the thin conductive layer and thin cover (option).

Body of nuclear reactor is shown in Fig.2. One contains: strong spherical body (shell) of reactor 1 (diameter about 0.3 – 3 m); the fuel cartridge 2 (It is described in Fig.1); holder (electric conductor) 3 of fuel cartridge; 4 – enter of compressed air (gas); exit of a hot compressed air (gas) after thermonuclear heating 5; electric voltage from condenser 6.

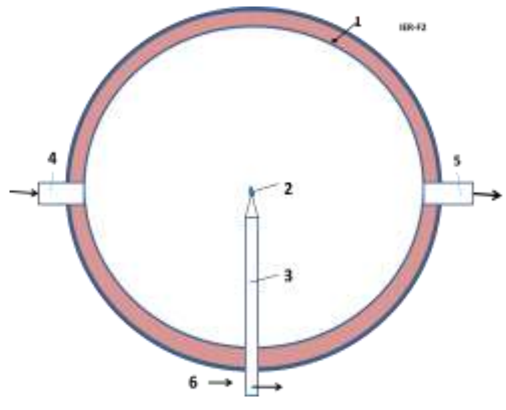


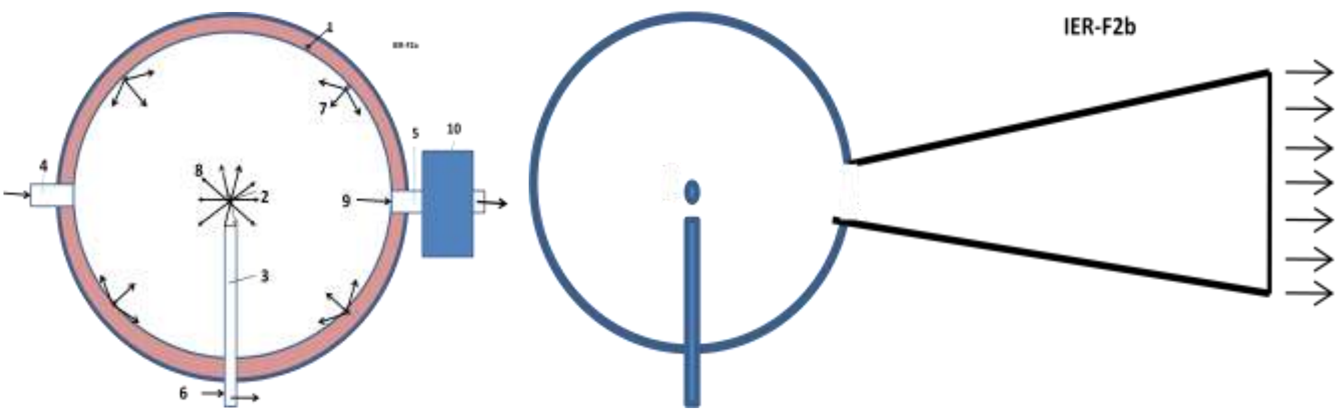
Fig. 2.AB thermonuclear electric reactor. *Notations*: 1 - strong spherical body (shell) of reactor (diameter about 0.3 – 3 m); 2 - the fuel cartridge (it is described in Fig.1); 3 - holder (electric conductor) 3 of fuel cartridge; 4 – enter of compressed air (gas); 5 – exit of a hot compressed air (gas) after thermonuclear heating; 6 – electric voltage from condenser.

The offered thermonuclear reactors work the next way (Figs. 1 – 3):
1) Cartridge Version 1 for an electric or mechanic energy.
The internal volume of reactor body is filled the atmospheric or compression air (enter 4 of Fig.2).

The fuel cartridge (Fig.1) lifts by holder 3 (Fig.2) into reactor body. Turn on the charged (up 15 -50 kV) electric condenser 7 (Fig 2). The electrons from the needle edge 6 (Fig.1) are accelerated to the conductive layer 2 (fig.1). They positive ionize and dissociate the fuel molecules (for example, D and T are contained into matter of layers 3-4 (in cartridge Version 1) or into volume 5 (in cartridge Version 2)). The positive ionized nucleus of the thermonuclear fuel (having small mass) are quick accelerated up very high temperature (up 15 – 50 keV) and collide at the needle edge. The heavy and slow molecules from cartridge layer 3 (fig.1) research the region at the needle edge later and compress the thermonuclear fuel and increase the fusion (reaction) time of the fuel nucleus at the needle edge. In results (as show computation) the fuel nucleus merge and produce a thermonuclear reaction. The thermonuclear reaction (explosive) heats the air into reactor body. For increasing the efficiency, work mass, decreasing explosive temperature and protection from neutrons, the liquid 7 (for example, water, fig. 3) may be injected into reactor.

2) In cartridge Version 3, the needle edge contains the very small pellet 6 having the thin conductive layer, thin cover and compressed fuel. The high energy outer fuel flow additional compress the pellet 6, penetrate through the pellet cover and heat the internal part of fuel.

After thermonuclear explosion the hot gas flow out into the magneto-hydrodynamic generator (MHG) 10 and produces electric energy or runs to the gas, steam turbine and produces an useful work (Fig. 3a). Or the hot compressed gas runs to rocket nozzle and produces the rocket trust (fig. 3b).



a ***b***

Fig.3. Final (industrial) work of Impulse Electric AB thermonuclear reactors. ***a***) Hot compressed gas from sphere runs to the magneto-hydrodynamic generator (MHG) 10 and produces electric energy or runs to gas turbine and produces an useful work (Fig. 3a). ***b***) Hot compressed gas runs to rocket nozzle and produces the rocket trust. *Notation*: 1 – 6 are same Fig.2; 7 – injection the cooling liquid (for example, water)(option); 8 – thermonuclear explosive of fuel pellet; 10 – MHG or gas (steam) turbine; 11 - exit of hot gas.

The main difference the offered electric reactor fromthe cumulative reactors (versions 2, 4) [2, 4] is type of explosive for getting the temperature, pressure and cumulative effect in fuel. On [1 -2] author used the chemical explosive. The offered reactor uses the strong electric field for acceleration, gettinghigh temperature and cumulative effect. The electric method leads topractically unlimited cheap power. In [2, 4] the explosive is located into main spherical body 1 (fig.1) (or gun in [2]). In [4] version 1 (fig.2, [4]) the explosive 3 is small and located in the special fuel cartridge (fig.2, [4]). In current version no special compression explosive. The pressure and high temperature of the fuel are reached the high voltage condenser . It easier and it is more comfortable in using.

The version 3 of current cartridge the fuel pullet is filling by the compressed gas fuel (up 100 atmosphere or more) and version 1 - 3 not has the explosive for an additional compressing of fuel. The fuel is compressed by cumulative fuel flow (in Version 1 by additional flow of heavy elements), heating only by strong electric charge of a condenser. The computation shows that is possible. In version 3, we can use the conventional pellet with frozen fuel.

AB Reactors are cooled using well-known methods between explosives or by an injection of water into sphere (fig. 3a).

Advantages of the suggested reactorsin comparison withICF Laser method.

The offered reactors and methods have the following advantages in comparison with the conventional ICF laser reactor:

1. The high voltage electric condenser allows reaching the needed thermonuclear temperature.
2. Cumulative, Impulse Electric a AB-reactors are cheaper by thousands of time because they do not have the gigantic very expensive laser or magnetic installations (see [1]-[4]).
3. They more efficiency because the laser installation converts only 1 -1.5% the electric energy into the light beam. In suggested AB reactors, the all underused energy remains in the spherical reactor and utilized in MHG or turbine. AB reactors cannot have coefficient *Q* (used energy) significantly less 1. Moreover, one has heat efficiency more than conventional heat engines because it has very high temperature and compression ratio. One can use as the conventional very high power engine in civil and military transportation.
4. The offered very important innovation (accelerating of exhaust rocket gas) allows increasing the top speed of the exhaust mass up very high speed. This makes this method available for thermonuclear rocket.
5. Electric AB-reactor gives temperature of the fuel much more than the current ICF laser installations.
6. This compression has longer time (up to 10^{-3} – 10^{-6} s) than a laser beam pressing (10^{-9} – 10^{-12} s), because mass of heavy molecules (layer 3 in fig.1) is many times (50 ÷ 100) heavier than fuel molar mass ($\mu = 2 \div 3$).This pressure is supported by gas flow and shock wave coming from moving heavy gas. This pressurereaches the center of needle edge (or fuel capsule) with high speed of heavy mass 3, (fig.1), (not sound speed as in laser pressure) increases the temperature, compressing and probability of thermonuclearreaction of the fuel.
7. The heavy mass 3 (layer in fig.1) (having high nuclear numbers $A \approx 100$ and $Z \approx 200$) not allow the nuclear particles easily to fly apart. That increases the reaction time and reactor efficiency.
8. The suggested AB-thermonuclear reactor is small (diameter about 0.5÷3 m or less up 0.3 m) light (massabout some ton or less up 150 kg) and may be used in the transport vehicles and aviation.
9. The water may protect the material of the sphere from neutrons.
10. It is possible (see computations) the efficiency of AB reactors will be enough for using as fuel only the deuterium which is cheaper then tritium in thousands times (One gram of tritium costs about 30,000 US dollars. One gram of deuterium costs 1$.).

Theory of current Thermonuclear Reactor

1. The following reactionsare suitable for thermonuclear fusion:

Table 1. Sutable reactions for thermonuclear fusion

(1)	D	+	T			^{4}He	(3.5 MeV)	+		n	(14.1 MeV)					
(2i)	D	+	D			T	(1.01 MeV)	+		p	(3.02 MeV)					*50%*
(2ii)						^{3}He	(0.82 MeV)	+		n	(2.45 MeV)					*50%*
(3)	D	+	^{3}He			^{4}He	(3.6 MeV)	+		p	(14.7 MeV)					
(4)	T	+	T			^{4}He		+	2	n	+ 11.3 MeV					
(5)	^{3}He	+	^{3}He			^{4}He		+	2	p	+ 12.9 MeV					
(6i)	^{3}He	+	T			^{4}He		+		p		+	n	+ 12.1 MeV		*51%*
(6ii)						^{4}He	(4.8 MeV)	+		D	(9.5 MeV)					*43%*
(6iii)						^{4}He	(0.5 MeV)	+		n	(1.9 MeV)	+	p	(11.9 MeV)		*6%*
(7)	D	+	^{6}Li		2	^{4}He	+ 22.4 MeV									
(8)	p	+	^{6}Li			^{4}He	(1.7 MeV)	+		^{3}He	(2.3 MeV)					
(9)	^{3}He	+	^{6}Li		2	^{4}He		+		p	+ 16.9 MeV					
(10)	p	+	^{11}B		3	^{4}He	+ 8.7 MeV									

Here are: p (protium), D (deuterium), and T (tritium) are shorthand notation for the main three isotopes of hydrogen.

For reactions with two products, the energy is divided between them in inverse proportion to their masses, as shown. In most reactions with three products, the distribution of energy varies. For reactions that can result in more than one set of products, the branching ratios are given.

Some reaction candidates can be eliminated at once. The D-^{6}Li reaction has no advantage compared to p-^{11}B because it is roughly as difficult to burn but produces substantially more neutrons through D-D side reactions. There is also a p-^{7}Li reaction, but the cross-section is far too low accepted possible for T_i> 1 MeV, but at such high temperatures, an endothermic, direct neutron-producing reaction also becomes very significant. Finally, there is also a p-^{9}Be reaction, which is not only difficult to burn, but ^{9}Be can be easily induced to split into two alphas and a neutron.

In addition to the fusion reactions, the following reactions with neutrons are important in order to "breed" tritium in "dry" fusion bombs and some proposed fusion reactors:

$$n + {}^6Li \rightarrow T + {}^4He \text{ ,} n + {}^7Li \rightarrow T + {}^4He + n \text{ .}$$

To evaluate the usefulness of these reactions, in addition to the reactants, the products, and the energy released, one needs to know something about the cross section. Any given fusion device will have a maximum plasma pressure that it can sustain, and an economical device will always operate near this maximum. Given this pressure, the largest fusion output is obtained when the temperature is selected so that $\langle\sigma v\rangle/T^2$ is a maximum. This is also the temperature at which the value of the triple product $nT\tau$ required for ignition is a minimum. This chosen optimum temperature and the value of $\langle\sigma v\rangle/T^2$ at that temperature is given for a few of these reactions in the following table.

Table 2. Optimum temperature and the value of $\langle\sigma v\rangle/T^2$ at that temperature

fuel	T [keV]	$\langle\sigma v\rangle/T^2$ [m³/s/keV²]
D-T	13.6	1.24×10^{-24}
D-D	15	1.28×10^{-26}
D-^{3}He	58	2.24×10^{-26}
p-^{6}Li	66	1.46×10^{-27}
p-^{11}B	123	3.01×10^{-27}

Note: that many of the reactions form chains. For instance, a reactor fueled with T and ^{3}He will create some D, which is then possible to use in the D + ^{3}He reaction if the energies are "right". An elegant idea is to combine the reactions (8) and (9). The ^{3}He from reaction (8) can react with ^{6}Li in reaction (9) before completely thermalizing. This produces an energetic proton which in turn undergoes reaction (8) before thermalizing. A detailed analysis shows that this idea will not really work well, but it is a good example of a case where the usual assumption of a Maxwellian plasma is not appropriate.

Any of the reactions above can, in principle, be the basis of fusion power production. In addition to the temperature and cross section discussed above, we must consider the total energy of the fusion products E_{fus}, the energy of the charged fusion products E_{ch}, and the atomic number Z of the non-hydrogenic reactant.

Specification of the D-D reaction entails some difficulties, though. To begin with, one must average over the two branches (2) and (3). More difficult is to decide how to treat the T and ^{3}He products. T burns so well in a deuterium plasma that it is almost impossible to extract from the plasma. The D-^{3}He reaction is optimized at a much higher temperature, so the burn-up at the optimum D-D temperature may be low, so it seems reasonable to assume the T but not the ^{3}He gets burned up and adds its energy to the net reaction.

Thus we will count the D-D fusion energy as E_{fus} = (4.03+17.6+3.27)/2 = 12.5 MeV and the energy in charged particles as E_{ch} = (4.03+3.5+0.82)/2 = 4.2 MeV.

Another unique aspect of the D-D reaction is that there is only one reactant, which must be taken into account when calculating the reaction rate.

With this choice, we tabulate parameters for four of the most important reactions.

Table 3. Parameters of the most important reactions

Fuel	Z	E_{fus} [MeV]	E_{ch} [MeV]	neutronicity
D-T	1	17.6	3.5	0.80
D-D	1	12.5	4.2	0.66
D-^{3}He	2	18.3	18.3	~0.05
p-^{11}B	5	8.7	8.7	~0.001

The last column is the *neutronicity* of the reaction, the fraction of the fusion energy released as neutrons. This is an important indicator of the magnitude of the problems associated with neutrons like radiation damage, biological shielding, remote handling, and safety. For the first two reactions it is calculated as $(E_{fus}-E_{ch})/E_{fus}$. For the last two reactions, where this calculation would give zero, the values quoted are rough estimates based on side reactions that produce neutrons in a plasma in thermal equilibrium.

Of course, the reactants should also be mixed in the optimal proportions. This is the case when each reactant ion plus its associated electrons accounts for half the pressure. Assuming that the total pressure is fixed, this means that density of the non-hydrogenic ion is smaller than that of the hydrogenic ion by a factor $2/(Z+1)$. Therefore, the rate for these reactions is reduced by the same factor, on top of any differences in the values of $\langle\sigma v\rangle/T^2$. On the other hand, because the D-D reaction has only one reactant, the rate is twice as high as if the fuel were divided between two hydrogenic species.

Thus, there is a "penalty" of $(2/(Z+1))$ for non-hydrogenic fuels arising from the fact that they require more electrons, which take up pressure without participating in the fusion reaction. There is, at the same time, a "bonus" of a factor 2 for D-D due to the fact that each ion can react with any of the other ions, not just a fraction of them.

We can now compare these reactions in the following table 4, below.

Table 4. Comparison of reactions

fuel	$\langle\sigma v\rangle/T^2$	penalty/ bonus	reactivity	Lawson criterion	power density
D-T	1.24×10^{-24}	1	1	1	1
D-D	1.28×10^{-26}	2	48	30	68
D-^{3}He	2.24×10^{-26}	2/3	83	16	80

p-^{11}B	3.01×10^{-27}	1/3	1240	500	2500

The maximum value of <σv>/T² is taken from a previous table. The "penalty/bonus" factor is that related to a non-hydrogenic reactant or a single-species reaction. The values in the column "reactivity" are found by dividing (1.24×10^{-24} by the product of the second and third columns. It indicates the factor by which the other reactions occur more slowly than the D-T reaction under comparable conditions. The column "Lawson criterion" weights these results with E_{ch} and gives an indication of how much more difficult it is to achieve ignition with these reactions, relative to the difficulty for the D-T reaction. The last column is labeled "power density" and weights the practical reactivity with E_{fus}. It indicates how much lower the fusion power density of the other reactions is compared to the D-T reaction and can be considered a measure of the economic potential.

Below aresome equation useful for computation:

2. The Deep of Penetration of outer radiation into plasma is

$$d_p = \frac{c}{\omega_{pe}} = 5.31\cdot 10^5 n_e^{-1/2} \quad . \text{[cm]} \qquad (1\text{-}1)$$

For plasma density $n_e = 10^{22}$ 1/cm^3 $d_p = 5.31\times10^{-6}$ cm.

3. The Gas (Plasma) Dynamic Pressure,p_k, is

$$p_k = nk(T_e + T_i) \quad \text{if} \quad T_e = T_k \quad \text{then} \quad p_k = 2nkT \qquad (2\text{-}1)$$

where $k = 1.38\times10^{-23}$ is Boltzmann constant; T_e is temperature of electrons, ^{o}K; T_i is temperature of ions,^{o}K. These temperatures may be different; n is plasma density, 1/m^3; p_k is plasma pressure, N/m^2.

4. The gas (plasma) ion pressure, p, is

$$p = \frac{2}{3} nkT, \qquad (3\text{-}1)$$

Here n is plasma density in 1/m^3.

*5. The magnetic p_m and electrostatic pressure, p_s,*are

$$p_m = \frac{B^2}{2\mu_0}, \quad p_s = \frac{1}{2}\varepsilon_0 E_S^2 \qquad (4\text{-}1)$$

where B is electromagnetic induction, Tesla; $\mu_0 = 4\pi\times10^{-7}$ electromagnetic constant; $\varepsilon_0 = 8.85\times10^{-12}$, F/m,is electrostatic constant; E_S is electrostatic intensity, V/m.

6. Ion thermal velocity is

$$v_{Ti} = \left(\frac{kT_i}{m_i}\right)^{1/2} = 9.79\times10^5 \mu^{-1/2} T_i^{1/2} \quad \text{cm/s} \ , \qquad (5\text{-}1)$$

where $\mu = m_i/m_p$, m_i is mass of ion, kg; $m_p = 1.67\times10^{-27}$is mass of proton, kg.

7. Transverse Spitzer plasma resistivity

$$\eta_\perp = 1.03\times10^{-2} Z \ln\Lambda T^{-3/2}, \quad \Omega\,\text{cm} \quad \text{or} \quad \rho \approx \frac{0.1\mathrm{Z}}{\mathrm{T}^{3/2}} \quad \Omega\,\text{cm} \quad , \qquad (6\text{-}1)$$

where $\ln\Lambda = 5 \div 15 \approx 10$ is Coulomb logarithm, Z is charge state.

8. Reaction rates <σ*v*> (in cm^3 s^{-1}) averaged over Maxwellian distributions for low energy (T<25 keV) may be represent by

$$(\overline{\sigma v})_{DD} = 2.33\times10^{-14}T^{-2/3}\exp(-18.76\,T^{-1/3})\quad \mathrm{cm^3s^{-1}}, \tag{7-1}$$
$$(\overline{\sigma v})_{DT} = 3.68\times10^{-12}T^{-2/3}\exp(-19.94\,T^{-1/3})\quad \mathrm{cm^3s^{-1}},$$

where T is measured in keV.

9. *The power density released in the form of charged particles* is

$$P_{DD} = 3.3\times10^{-13}n_D^2(\overline{\sigma v})_{DD},\quad \mathrm{W\ cm^{-3}}$$
$$P_{DT} = 5.6\times10^{-13}n_D n_T(\overline{\sigma v})_{DT},\quad \mathrm{W\ cm^{-3}} \tag{8-1}$$
$$P_{DHe^3} = 2.9\times10^{-12}n_D n_{He^3}(\overline{\sigma v})_{DHe^3},\quad \mathrm{W\ cm^{-3}}$$

Here in P_{DD} equation it is included D+T reaction.

10. Reaction rates are presented in Table 5 below:

Table 5. Reaction rates <σv> (in cm^{-3} s^{-1}) averaged over Maxwellian distributions

Tempera-ture, keV	D+D, (1a + 1d)	D+T , (2)	D+He, (3)
1.0	1.5×10^{-22}	5.5×10^{-21}	10^{-26}
2.0	5.4×10^{-21}	2.6×10^{-19}	1.4×10^{-23}
5.0	1.8×10^{-19}	1.3×10^{-17}	6.7×10^{-21}
10.0	1.2×10^{-18}	1.1×10^{-16}	2.3×10^{-19}
20.0	5.2×10^{-18}	4.2×10^{-16}	3.8×10^{-18}
50.0	2.1×10^{-17}	8.7×10^{-16}	5.4×10^{-17}
100.0	4.5×10^{-17}	8.5×10^{-16}	1.6×10^{-16}
200.0	8.8×10^{-17}	6.3×10^{-16}	2.4×10^{-16}
500.0	1.8×10^{-16}	3.7×10^{-16}	2.3×10^{-16}
1000.0	2.2×10^{-16}	2.7×10^{-16}	1.8×10^{-16}

Issue: AIP, Desk Reference, Thied Edition, p.644.

Theory, computation and estimation of Electric, Cumulative and Impulse AB-reactors and comparison one with current ICF.

Estimation of Laser method (ICF).

For comparison the laser and offer Electric, Cumulative and Impulse AB methods, we estimate the current ICF laser method.

Typical laser installation for ICF has the power 5 MJ and deliver to pellet about 20÷50 kJ energy. The pullet has the 1 – 10 mg liquid (frozen) fuel D+T (density 200 kg/m^3), diameter of the fuel pullet about1- 2 mm, diameter of an evaporative coating 4 – 10 mm.

Let us take the delivered energy E = 50 kJ, volume of the coating v = 5 mm^3, specific weight of coating γ = 400 kg/m^3 (molar weight μ = 10).

For these data and instant delivery of laser energy the maximum pressure in cover is

$$p = \frac{E}{v} = \frac{5\times10^4}{5\cdot10^{-9}} = 10^{13}\,\frac{N}{m^2} = 10^8\,\mathrm{atm} \tag{1-2}$$

But we don’t know what part this pressure transfer to the fuel pellet.

Number of nuclear in 1 m^3 of covering is

$$n = \frac{\gamma}{\mu m_p} = \frac{0.4\cdot10^3}{10\cdot1.67\cdot10^{-27}} = 2.4\cdot10^{28}\quad [m^{-3}] \tag{2-2}$$

Here m_p=1.67·10^{-27} is mass of nucleon (proton) [kg].

Temperature of evaporating cover is

$$T = \frac{p}{nk} = \frac{10^{13}}{2.4\cdot 10^{28} 1.38\cdot 10^{-23}} = 3\cdot 10^7 \quad [K] \tag{3-2}$$

Here k = 1.38×10^{-23} Boltzmann constant, J/^{o}K.

Speed of evaporated covering is

$$V = \left(\frac{8kT}{\pi\mu m_p}\right)^{0,5} = \left(\frac{8\cdot 1.38\cdot 10^{-23} 3\cdot 10^7}{3.14\cdot 10\cdot 1.67\cdot 10^{-27}}\right)^{0.5} = 2.51\cdot 10^5 \ m/s = 251\, km/s \tag{4-2}$$

Time of evaporating for thickness of covering l = 2·10^{-3} m is

$$t = \frac{l}{V} = \frac{2\cdot 10^{-3}}{2.51\cdot 10^5} = 8\cdot 10^{-9} \quad s \tag{5-2}$$

Let us to consider now the process into pellet.

The density of fuel particles is

$$n_f = \frac{\gamma}{\mu m_p} = \frac{200}{2.5\cdot 1.67\cdot 10^{-27}} = 4.8\cdot 10^{28} \quad \frac{1}{m^3} \tag{6-2}$$

where μ = 2.5 is average molar mass of fuel D+T.

The frozen (liquid) fuel, after converting in gas, has a temperature of about T = 4 K.

The pressure average speed $V_n$of particles afterconversion of the fuel into gas (plasma) and sound speed $V_f$to fuel gas at temperature 4K are:

$$p_f = n_f kT = 4.8\cdot 10^{28}\times 1.38\cdot 10^{-23}\times 4 = 2.65\cdot 10^6 \quad N/m^2 = 26.5 \quad atm,$$

$$V_n = \left(\frac{8kT}{\pi\mu m_p}\right)^{1/2} = \left(\frac{8\cdot 1.38\cdot 10^{-23}\cdot 4}{3.14\cdot 2.5\cdot 1.67\cdot 10^{-27}}\right)^{1/2} = 183 \ \frac{m}{s}, \tag{7-2}$$

$$V_f = \left(\frac{p_f}{\rho_f}\right)^{1/2} == \left(\frac{2.65\cdot 10^6}{200}\right)^{1/2} = 115 \quad m/s.$$

Additional fuel pressure in ***center*** of pellet from two opposing sound wave bump-up is

$$p_s = \rho_f (2V_f)^2/2 = 200\cdot(2\cdot 115)^2/2 = 5.3\cdot 10^6 \quad N/m^2 = 53 \quad atm. \tag{8-2}$$

Fuel temperature in ***center*** of small mass pellet where two opposing sound (shock) wave bump-up happens is

$$T = \frac{\pi\mu m_p (V_n + V_f)^2}{8k} = \frac{3.14\cdot 2.5\cdot 1.67\cdot 10^{-27}(183+115)^2}{8\cdot 1.38\cdot 10^{-23}} = 10.5\, K \tag{9-2}$$

In reality, the full pressure and temperature in center of capsule is much more. We compute ONLY the sound wave. Any shock wave becomes fast at short distance the sound wave. However, in our case this computation is very complex.

Current inertial reactors have the maximal rate of fuel compressing in center of pellet about

$$\xi \approx 600 \,. \tag{10-2}$$

Criterion of ignition (for radius of pullet R_o = 0.02 sm and solid or liquid fuel ρ_o= 0.2 g/cm^3) is

$$\rho R = \rho_o R_o \xi^{2/3} = 0.2\cdot 0.02\cdot (600)^{2/3} = 0.28 < 1 \tag{11-2}$$

where ρ in g/cm^3, R in cm.That value is not enough (0.28 < 1).

You can imagine – with just a small effort and we will fulfill the criterion of ignition! Look your attention in very low temperature of fuel (9-2). For this temperature, the criterion may be wrong, or area of the ignition located into center of pullet may be very small, that energy is very few for ignition of all fuel?

Estimation of some parameters theElectric Cumulative AB reactor.

The proposed Electric Cumulative AB Reactor accelerates the fuel 4 and layer3 from a heavy material by a strong electric field (Fig. 1, Version 1 - 2). If part of fuel into pellet (Version 3), the outer flow of fuel and heavy material bumps the fuel pellet contained nuclear fuel, compresses and heats the pellet up to very high values, producing a nuclear reaction.Inlike [1 – 3] the cumulative explosionis produced not chemical explosive but a strong electric impulse.

Below is not mega-project. Instead, below,isthe estimations of the typical parameters of electric cumulative AB reactors.

1. Suitable thermonuclear reactions.

The corresponding reactions are:

$D + T \rightarrow {}^4He$ (3.5MeV) + n (14.1MeV);

$D + D \rightarrow T$ (1.01MeV) + p (3.02MeV) 50%

$D + D \rightarrow {}^3He$(0.82MeV) + n (2.45MeV) 50%

The deuterium cannot be used in the laser reactor because one requests in 100 times more ignition criterion then D + T. But one may be used in AB reactors (Fig.6) with an additional heating by electric

The ${}^3He$ is received in deuterium reaction may be used in next reactions:

$D + {}^3He \rightarrow {}^4He$ (3.6MeV) + p (14.7MeV);

${}^3He + {}^3He \rightarrow {}^4He$ +2p (12.9MeV).

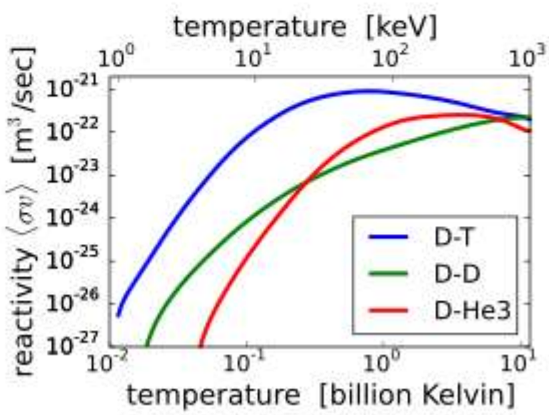


Fig.4. Reactivity is requested for thermonuclear reaction.

They produce only high-energy protons which can be directly converted in electric energy. Last reactions do not produce radio isotopic matters (no neutrons).

Reaction D + D has the other distinct advantages:

1. One produces the protons which energy can be converted directly to electric energy.
2. One produces the tritium which is expensive and may be used for thermonuclear reaction.
3. One produces less and low energy neutrons which create radioactive matters.

The other important advantage is using the pellets with compression gas fuel. Let us take a micro-balloon (pellet) having fuel gas with p_o= 100 atm., radius 0.05 cm., temperature 300K. The mass fuel will be 0.52 mg.

Compressed micro-balloon (pellet) is more comfortable for working because it is unnecessary to store the fuel at lower (frozen)) temperature.

2. Cumulative nucleus speed, temperature and pressure in center of fuel cartridge.

When we turn on the high voltage electric impulse, the power electron flow from the needle edge is vaporized, ionized and dissociated the fuel.

The average ion (nuclear) temperature. The average voltage U = 15 kV of condenser is accelerated fuelion in vacuum (version 1-2). The ion temperatureis

$$T = 15\cdot 10^3 \cdot 1.18\cdot 10^4 = 177\cdot 10^6\ K\,.$$

In version 3 the half of this temperature will have the fuel gas is filled the cartrige. The need condenser voltage must be more in two times.The energy of ionization and dissociation is small (3 ÷ 15 eV) in comparison with energy from acceleration (15 ÷ 100)keV. We can neglect it. The full ionized ions are moving as one whole.That means no gas resistance for fuel ion acceleration. Any atom in internal space of cartridge will be ionized and accelerated.

The average speed of ionsand electrons for U = 15kV is:

$$V_i = \sqrt{\frac{2eU}{\mu m_p}} = \sqrt{\frac{2\cdot 1.6\cdot 10^{-19}15\cdot 10^3}{2.5\cdot 1{,}67\cdot 10^{-27}}} \approx 10^6\ \frac{m}{s}\,, \quad V_e = \sqrt{\frac{2eU}{\mu m_e}} = \sqrt{\frac{2\cdot 1.6\cdot 10^{-19}15\cdot 10^3}{2.5\cdot 9.1\cdot 10^{-31}}} \approx 4.6\cdot 10^7\ \frac{m}{s} \quad ,(13=2)$$

Here e =1.6·10^-19^ is charge of ion, C; U is condenser voltage, V; μ is relative mass of fuel D+T; m_p= 1.67·10^{-27}is proton weight, kg, m_e= 9.1·10^{-31}is electron mass, kg.

The average time of ion and electron moving in distance L = 5 mm and speed V = 10^6 m/s are:

$$T_i = \frac{L}{V_i} = \frac{5\cdot 10^{-3}}{10^6} = 5\cdot 10^{-9}\ s, \quad T_e = \frac{L}{V_e} = \frac{5\cdot 10^{-3}}{4.6\cdot 10^7} = 1.1\cdot 10^{-10}\ s \quad , \qquad (14\text{-}2)$$

3.Maximal deviation of fuel ion from cartridge centeris

$$r_a = V_0 T_i = 1750\cdot 5\cdot 10^{-9} = 8.75\cdot 10^{-6}\ m\,, \qquad (15\text{-}2)$$

whereV_0 is speed of nucleon for temperature at 300 K.

4. Ion free path in the center of the cartridge

$$l = \frac{1}{\sqrt{2}\pi n_0 \sigma^2} = \frac{1}{\sqrt{2}\cdot 3.14\cdot 2.4\cdot 10^{25}(5\cdot 10^{12})^2} = 3.76\cdot 10^{-4}\ cm \qquad .(16\text{-}2)$$

Here $n_o = N/v$ = 2.4·10^{19}/10^{-6}cm^{-3} is density of fuel ion in center of cartridge (v is volume 1 cm^3), σ is cross-section ion diameter, cm^2. Than means, the ions will collisions many times at center of the cartridge.

5. *Thermonuclear energy*. One/tenth mg (10^{-7} kg) of thermonuclear fuel D+T has energy:

Number of nucleus:

$$n_1 = \frac{M}{\mu m_p} = \frac{10^{-7}}{2.5\cdot 1.67\cdot 10^{-27}} = 2.4\cdot 10^{19} \qquad (17\text{-}2)$$

One pair of nuclear D+T produces energy E_1 = 17.6 MeV. The n_1 nuclear particles contain the energy

$$E = 0.5\ n_1 E_1 = 0.5\cdot 2.4\cdot 10^{19} 17.6\cdot 10^6 = 21.1\cdot 10^{25}\ eV = 21.1\cdot 10^{25} 1.6\cdot 10^{-19}\ J = 3.38\cdot 10^7\ \text{J} \qquad (18\text{-}2)$$

One pair of nuclear D+D produces energy E_1 = 3.64 MeV. The $n_{1=}$ 0.3·10^{19} nuclear particles contain the energy

$$E = 0.5\ n_1 E_1 = 0.5\cdot 3\cdot 10^{19} 3.64\cdot 10^6 = 5.46\cdot 10^{25}\ eV = 5.46\cdot 10^{25} 1.6\cdot 10^{-19} \approx 8.74\cdot 10^6\ \text{J} \qquad (19\text{-}2)$$

If coefficient efficiency of the Electric Cumulative AB Reactor is η = 0.3, 0.1 mg of fuel T+D produces the energy 10 million joules, D+D produced 2.62 million joules. If we make one explosion per sec, installation has the power of 10 million watts (T+D). The part of this energy will be produced inside fuel microcapsule fuel pellet (3.5 MeV from ^{4}He, E = 5.6·10^{7}J) the most of energy (14.1 MeV from neutrons, E = 22.6 J) will be produced into the big containment sphere.

Conventional coefficient of nuclear reactor efficiency is about 0.3÷ 0.5, the steam (gas) turbine is about 0.9.

6. *Estimation of pressure and temperature after nuclear explosion in reactor (more precisely, inside reactor sphere).*

Let us to find the pressure and temperature after thermonuclear explosive the 0.1 mg fuel D+T into reactor having sphere 1 m^3 filled by air.

Number of nuclear particles in sphere 1 m^3 is

$$n_n = \frac{M}{\mu m_p} = \frac{10^{-7}}{2.5\cdot 1.67\cdot 10^{-27}} = 2.4\cdot 10^{19} \quad \frac{1}{m^3} \qquad (20\text{-}2)$$

Full thermonuclear energy (η = 1):

$$E_n = 0.5 n_n E_1 = 0.5\cdot 2.4\cdot 10^{19} 17.6\cdot 10^6 = 21.1\cdot 10^{25}\ \mathrm{eV} = 3.38\cdot 10^7\ \mathrm{J}\ . \qquad (21\text{-}2)$$

Number of air particles with air density ρ = 1.225 kg/m^3 in pressure p = 1 atm. $\mu \approx 28$ is

$$n_o = \frac{M}{\mu m_p} \approx \frac{1.225}{28\cdot 1.67\cdot 10^{-27}} = 2.6\cdot 10^{25} \quad \frac{1}{m^3}\ . \qquad (22\text{-}2)$$

If coefficient efficiency of thermonuclear reaction is η = 0.3 in volume 1 m^3:

$$p = \frac{\eta E_n}{v} = \frac{0.3\cdot 3.38\cdot 10^7}{1} = 1\cdot 10^7 \approx 10^7\ \frac{\mathrm{N}}{\mathrm{m}^2} = 100\,\mathrm{atm}\ . \qquad (23\text{-}2)$$

Total pressure– nuclear explosive is $p \approx 100$ atm.

Temperature of gas mixture of explosive plus nuclear fuel is

$$T = \frac{p}{(n_0 + n_n)k} = \frac{10^7}{(2.6\cdot 10^{25} + 2.4\cdot 10^{19})\cdot 1.38\cdot 10^{-23}} = 27.9\cdot 10^3\ \mathrm{K} \qquad (24\text{-}2)$$

If we increase the initial pressure into reactor body up 10atm, that the temperature decreases to 2790K.

The same temperature is in a combustion chamber of conventional engine of the internal combustion.

We can use the conventional cooling system.

The same method may be used for estimation of injection water into installation body or any garbage material in a space ship.

7. Possibility charging the condenser .

If we use the fuel D+D the our reactor can directly produce protons having E_1 = 3.03 MeV. For fuel 10^{-7} kg ($N = 3\cdot 10^{19}$) in one explosion (cycle) and efficiencyη = 0.5 that gives the electric energy

$$E = 0.5\eta E_1 eN = 0.5\cdot 0.5\cdot 3.03\cdot 10^6 1.6\cdot 10^{-19} 3\cdot 10^{19} = 3.6\cdot 10^6\ J$$

This energy in 50 times more than energy $72\cdot 10^3$ J, which is requests for heating fuel for thermonuclear reaction.

8. *Thickness of sphere cover*. Assume the spherical coverof reactor is made from conventional steel having safety tensile stress σ = 50 kg/mm^2= $5\cdot 10^8$ N/m^2. The full tensile force is $F = \pi r^2 p = 3.14\cdot 0.5^2\cdot 10^7$ = $0.785\cdot 10^7$ N. Requested area of steel is $S_r = F/\sigma = 0.785\cdot 10^7/5\cdot 10^8$ =0.0157 m^2. The thickness of sphere wall is $\delta = S_r/2\pi r = 0.0157/2\cdot 3.14\cdot 0.5 = 0.005$ m. Mass of sphere is $M_c \approx \gamma S_s \delta = 7800\cdot 3.14\cdot 0.005 = 122.5$ kg. Here $S_s = 4\pi r^2 = 4\cdot 3.14\cdot 0.5^2 = 3.14$ m^{2}is average surface of sphere.

If we use the more strong material for sphere wall, for example: 1μm iron whisker having safety tensile stress $\sigma \approx 400$ kg/mm^2= $4\cdot 10^9$ N/m^2, we decrease the sphere's mass by 4 – 8 times. We can also make the sphere wall from composite materials (example: an artificial fiber carbon or glass having safety stress $\sigma \approx 100 \div 150$ kg/mm^2 and density $\gamma = 1500 \div 2700$ kg/m^3).

9. *Cooling the sphere by water*. If explosions are very frequent, we then can decrease the wall or/and gas temperature by injection of the chilled or room temperature water. The water also protects our installation from high-energy neutrons in other words, it behaves as a shielding materials.

Let us estimate the amount of water which decreases the temperature and pressure of gas (at most steam H_2O) into sphere for magnitudes acceptable for current steam turbines: T = 400^{o}C = 672 K. The critical point of water (triple point) is T = 273^{o}C, p = 22 MPa.

Heating 1 kg water from 20°C to 100°C requests energy $E = C_p\Delta T = 4.19\cdot 80 = 333$ kJ, evaporation – r = 2260 kJ, heating of steam up 400°C - $E = C_p\Delta T = 1.05\cdot 300 = 315$ kJ. Total amount of water heat energy is $E_w = 333 + 2260 + 315 = 2908$ kJ/kg. Total mass of water for nuclear efficiency $\eta = 1$ equals $M_w = E/E_w = 3.4\cdot 10^7/2.9\cdot 10^6 = 11.7$ kg. For $\eta = 0.3$ $M_w = 3.5$ kg. The 2 – 3 cm of water thickness protects the installation from high energy of neutrons produced by reaction D+T.

Unfortunately, the injection of water before decompressing strongly decreases the efficiency of installation.

10. *Run protons and heavy nuclear particles*.

The physic directory by Kikoin, Moscow, 1975, p. 953[11] gives the following equation for running the protons and charged heavy particles inside gas at pressure 1 atm

$$R_x(E) = \frac{m_x}{m_p} R_p\left(\frac{m_p}{m_x}E\right) \quad , \qquad (25\text{-}2)$$

Where R_x is runof the investigated particles, m_x is mass of investigated particles, m_p is mass of proton, R_p is run of known particles in a known environment, E is energy of particles in MeV. The run of proton in H_2 at pressure 1 atmosphere is in Table 6:

Table 6. Run (range) of proton in gas H_2 at pressure 1 atmosphere

Energy E [MeV]	1	10	100
Run R [cm]	10	$5\cdot 10^2$	$2\cdot 10^4$

For particles ^{4}He (3.5 MeV) in reaction D+T under the pressure $p = 10^7$atmosphere the run is

$$R_x(E) = \frac{m_x}{m_p} R_p\left(\frac{m_p}{m_x}E\right)/\,p \approx \frac{4}{1} R_p\left(\frac{1}{4}1\cdot 3.5\right)/10^8 \approx 4\cdot 10/10^7 = 4\cdot 10^{-6}\ cm \approx 4\cdot 10^{-5}\ \text{mm} \qquad (26\text{-}2)$$

The closed run has proton.

That means the all energy of the charges particles after nuclear reaction is used for heating other “cold” particles. If probability of an initial reaction is more than 10 keV/3500 ke V= 1/ 350, the chain reaction and ignition will occur .

In the Electric Cumulative AB Reactor these conditions are in *whole* fuel capsule, in laser reactor of many times lower conditions may be *only* in center of fuel capsule (collision of the imposed shock waves). If reacted particles run out the center of capsule, its energy will wasted.

The run way of neutrons is large and very complex function of energy and conditions of Environment.

11.*Converting the nuclear energy ofElectric Cumulative AB reactor to electric, mechanical energy or a rocket thrust.*

The best means for converting a Cumulative AB Reactor nuclear energy is magneto hydrodynamic electric generator (MHD-generator) which converts with high efficiency the high temperature and high pressure plasma directly in electric energy. Together with capacitors one can produces continuous electric currency. Impulse work of reactor allows to cool the reactor by injection the cooler (or conventional cooling) and protect the Electric Cumulative AB Reactor installation from very high temperature.

The second way for converting an Electric Cumulative AB Reactor nuclear energy is conventional heat exchanger and gas turbine. As cooler may be used the FLiBe – melted mix of fluoride salts of lithium and beryllium.

The third way is injection of water inside sphere and steam turbine as description over.

12. *Using the Electric BC umulativereactor as an impulse space rocket engine.*

There are good prospects (possibility) to use the suggested Electric Cumulative AB Reactor as an impulse rocket engine.

Assume the fuel energy is 10^8 J and mass of cartridge is 5 gram. If plasma will flow from reactor to space the average speed $V$of jet is

$$\text{From}\quad E=\frac{mV^2}{2}\quad \text{we get}\quad V=\left(\frac{2E}{m}\right)^{1/2}=\left(\frac{2\cdot 10^8}{5\cdot 10^{-3}}\right)^{1/2}=2\cdot 10^5\ \frac{\text{m}}{\text{s}}. \qquad (27\text{-}2)$$

Here E=10^8 is nuclear energy in one impulse one mg nuclear fuel, J; m= 5 g is the mass injected to outer space (fuel cartridge), kg.

Received speed V = 200 km/s is in many times more than a current exhaust chemical speed 3 km/s. If of space apparatus has mass m_2 = 1 ton, the ship speed changes in $V_2 = (m/m_2)V$ = 1 m/s in one impulse.If we spend 10 kg of fuel cartridges, the apparatus get speed 2 km/s.

More importantly, the next possibility is of the rocket powered by the Electric Cumulative AB Reactor. Any matter from any planets, asteroids, space body may be used as fuel (or addition to emission) for increasing the derivation of impulses. For example, assume the captured solid object moving through spaceis composed of some water, and we filled rocket tanks using that mined planet, comet or asteroid water. From (35-2) and Law of equal impulse we have from every impulse

$$V_2 \approx (2Em_1)^{1/2}/m_2 = (2\cdot 10^8\cdot 16)^{1/2}/10^3 = 56.6 \quad m/s. \qquad (28\text{-}2)$$

Here V_1 is add speed m_1 mass jet kg, m_1 = 16 kg of water; m_2 is mass of space apparatus.

13. *Estimation of the neutron penetration*

$$l = 1/n\sigma, \qquad (29\text{-}2)$$

Where l is path of penetration, cm; n is density of material, 1/cm^3; $\sigma=10^{-24}$ cm^2 is cross section of the nuclear. For steel l = 12 cm, for compressed air up 100 atm the l = 410 cm.

14. *Requested thickness of the spherical shell* is

$$\frac{D}{d}=\left(\frac{p}{\sigma}+1\right)^{0.5}. \qquad (30\text{-}2)$$

Where D is outer diameter of spherical shell, d is inner diameter of spherical shell, p is pressure, atm; σ is safety tensile stress kg/cm^2. Example, if p = 10kg/mm^2, σ = 50 kg/mm^2, then D/d ≈ 1.1.

Detail Estimation of Electric Cumulative reactors for transportation engine

1. **Estimation of nuclear energy (power).** Let us make more detail estimation the Electric Cumulative reactors for engine of transport vehicle having the fuel pellet 0.1 mg($M_f = 10^{-7}$ kg) with fuel D+T and D+D.

Estimation of energy the D+T fuel for the coefficient efficiency η =0.5 is;
The couple nuclei T+D produces nuclear energy E_1 = 17.6 MeV.
Number N of fuel nuclei's is:

$$N=\frac{M_f}{\mu m_p}=\frac{10^{-7}}{2.5\cdot 1.67\cdot 10^{-27}}=2.4\cdot 10^{19}.$$

Here μ is averagerelative mass of D+T; m_p is mass of proton, kg.
The nuclear energy of 0.1 mg D+T fuel in 1 Hz is

$$E=0.5E_1 eN\eta = 0.5\cdot 17.6\cdot 10^6\cdot 1.6\cdot 10^{-19} 2.4\cdot 10^{19}\cdot 0.5 = 16.9\cdot 10^6 \approx 17\ MJ/Hz.$$

Here $e = 1.6\cdot 10^{-19}$ C is charge of electron, C.

That is power energy of the 2 ÷ 5 power aviation turbo-engines. If one cycle in second (1Hz) is not enough, we can decrease the frequency. The piston engine has up 50-70 revolution per second, the high speed aviation gun up 30 shots in second.

If we use the D+D fuelhaving single energy E_1 = 3.65 MeV , μ = 2, the nucler energy is aproximetely in 5 times less because E_1 is less.

2. **Size of cartridge and pellet**. Let us estimate the size of the electric cumulative cartridge having an internal diameter d = 10 mm. The thickness δ of wall is 0.5 mm. Outer diameter of cartridge for safety tensile stress 100 kg/mm^2 is $D\approx$ 11 mm.

Let us estimate the compressed **pellet** having gas mass $M = 0.5\cdot10^{-7}$ kg (Version3, the other accelerated fuel is located in cartridge), pressure p = 300 atm $=3\cdot10^7$ N/m^2 and T = 300 K. Specific density the gas D+D, D+T in compression p = 1atm is ρ_o= 0.1kg/m^3,atm. The internal radius of gas pellet is:

$$r=\left(\frac{3M}{4\pi p\rho_0}\right)^{1/3}=\left(\frac{3\cdot0.5\cdot10^{-7}}{4\cdot3.14\cdot3\cdot10^2 0.1}\right)^{1/3}\approx0.74\cdot10^{-3}m\approx0.74\,mm\,.$$

The relative outer diameter of pellet for pressure p = 3 kg/mm^2 and the safety tensile stress of the pellet cover σ = 50 kg/mm^2 with according (30-2) is

$$\frac{D}{d}=\left(\frac{p}{\sigma}+1\right)^{0.5}=\left(\frac{3}{50}+1\right)^{1/2}=1.03\,.$$

3.Nuclear processes in to pellet. After electric cumulative explosive into cartridge the mass of 10^{-7} kg fuel D+T into pellet having diameter d = 1 mm($v\approx 0.8\cdot10^{-6}$ cm^3) after electric cumulative compressing is

$$n=\frac{m}{\mu m_p v}=\frac{10^{-7}}{2.5\cdot1.67\cdot10^{-27}(0.8\cdot10^{-6})}=3\cdot10^{25}cm^{-3}\,.$$

Where p is pressure after cumulative compressing, N/m^2;v is a pelletvolume, cm^3;m_p is mass of proton, kg. Density of D+D fuel is $n = 3.75\cdot10^{25}$ cm^{-3}.

Time of fuel combustion for T = 15 keV is

$$\text{For D+T}\quad t=\frac{0.5\eta E_1}{5.6\cdot10^{-13}n<\sigma v>}=\frac{0.5\cdot0.5\cdot2.82\cdot10^{-12}}{5.6\cdot10^{-13}3\cdot10^{25}2.65\cdot10^{-16}}=1.58\cdot10^{-10}\ s,$$

$$\text{For D+D}\quad t=\frac{0.5\eta E_1}{3.3\cdot10^{-13}n<\sigma v>}=\frac{0.5\cdot0.5\cdot0.58\cdot10^{-12}}{5.6\cdot10^{-13}3.75\cdot10^{25}3.2\cdot10^{-18}}=3.7\cdot10^{-9}\ s,$$

Where η is coefficient efficiency, E_1 is energy couple nucleis (for D+T $E_1 = 17.6\text{MeV}\cdot1.6\cdot10^{-19}$= $2.82\cdot10^{-12}$ J; for D+D E_1=3.65MeV= $0.58\cdot10^{-12}$ J). Here we used Eq. (8-1) and Table 5.

4.Estimation of electric condenser. For heating of fuel we use the short strong electric impulse. For impulse the electric condenser may be used. Let us to estimate the condenser parameters for getting the fuel temperature T = 15 keV.

If fuel mass is M = 0.1 mg = 10^{-7}kg, the number of nucleus for D+T is

$$N=\frac{M}{\mu m_p}=\frac{10^{-7}}{2.5\cdot1.67\cdot10^{-27}}=2.4\cdot10^{19}\,.$$

For D+D the $N = 3\cdot10^{19}$.

The energy W is needed for heating the fuel D+T up temperature T = 15 keVis

$$W=NT\cdot e=2.4\cdot10^{19}15\cdot10^3 1.6\cdot10^{-19}\approx60\,kJ\,.$$

For heating D+D fuel is W = 72 kJ.

The minimal specific weight of conventional conductor according [8] p. 368 is γ = 2kJ/kg. Consequently, the requested mass of condenser is about 30 – 36 kg. But if we can use the advanced supercapacitor (γ = 10 kJ/kg) or ultra-capacitor (γ = 20 kJ/kg) or capacitor EEStor, having claimed capacity γ = 1000 kJ/kg, we can decreased the capacitor mass. In any case, the capacitor mass is small part of thermonuclear engine.

5. **Estimation of capacitor discharge**.

Electric resistance of a copper wires connected condenser to cartidgeis

$$R = \rho \frac{l_0}{s} = 1.75 \cdot 10^{-6} \frac{400}{1} = 7 \cdot 10^{-4} \approx 10^{-3}\ \Omega .$$

Where l_0= 400 cm is length of wire, cm; s= 1 cm^{2}is cross-section area of wire, sm^2.

The plasma resistance into cartridge we can neglect.

Time of the condenser discharge for initial voltage U = 30 kV

$$t = \frac{RW}{U^2} = \frac{10^{-3} 60 \cdot 10^3}{(30 \cdot 10^3)^2} = 6.75 \cdot 10^{-8}\ s$$

The time of discharge must be more than time of the full thermonuclear reaction (10^{-9} s).

The average electric currency in cartridge

$$I = \frac{W}{Ut} = \frac{6 \cdot 10^4}{3 \cdot 10^4 6.75 \cdot 10^{-8}} = 0.3 \cdot 10^8\ A .$$

Capacity of condenser

$$C = \frac{t}{R} = \frac{6.75 \cdot 10^{-8}}{10^{-3}} = 6.75 \cdot 10^{-5}\ F .$$

The specific energy weight γ_c [J/kg] of the condenser may be estimated by formulas

$$\gamma_c = \frac{\varepsilon_0 \varepsilon E_q^2}{\gamma} .$$

Where ε_o= 8.85$\cdot 10^{-12}$ F/m is electric constant; $\boldsymbol{\varepsilon} \approx$ 3 dielectric constant; $E_q \approx$ 160 ÷ 640 MV/m is safety electric stress of isolator; $\gamma \approx$ 1000 ÷ 3000 kg/m^3 is specific weight of isolator. The $\gamma_c \approx$ 3 kJ/kg.

6. Magnetic pressure from electric currency.

a) Pellet having electric cumulative compressing has initial currency I = 3$\cdot 10^7$ A, radius of pellet (edge of needle)before compressing r = 0.5$\cdot 10^{-3}$ m has magnetic intensity H and magnetic pressure p:

$$H = \frac{I}{2\pi r} = \frac{3 \cdot 10^7}{2 \cdot 3.14 \cdot 0.5 \cdot 10^{-3}} \approx 10^{10}\ \frac{A}{m},$$

$$p = \frac{\mu_0 H^2}{2} = \frac{4\pi \cdot 10^{-7} (10^{10})^2}{2} = 6.28 \cdot 10^{13}\ \frac{N}{m^2} = 6.28 \cdot 10^8\ atm .$$

That is closed to electric cumulative pressure for diameter capsule (center area) r = 0.5 mm (p = 6$\cdot 10^8$ atm.).

The electric intensity E and electric pressure near center r = 0.5 mm is

$$E = \frac{U}{r} = \frac{30 \cdot 10^3}{0.5 \cdot 10^{-3}} = 6 \cdot 10^7\ \frac{V}{m}, \quad p = \varepsilon_o \frac{E^2}{2} = 8.85 \cdot 10^{-12} \frac{(6 \cdot 10^7)^2}{2} = 1.6 \cdot 10^4\ \frac{N}{m^2} = 0.16\ atm. .$$

As you see the electrostatic pressure we can neglect.

7. The heating problem of a needle egde.

Let us estimate the cooling of needle edge.Assume the needle edge is made from copper (ρ = 1.75$\cdot 10^{-6}$ Ohm$\cdot$cm) and has the length l = 0.5 cm and cross-section area$s$ = 0.04 cm^2. The electric resistance of edge is

$$R = \rho \frac{l}{s} = 1.75 \cdot 10^{-6} \frac{0{,}5}{0.04} = 2.2 \cdot 10^{-5}\ Ohm .$$

Let us take the average condenser dischargetime $t = 6{,}75 \cdot 10^{-8}$ s and electric currency $I = 3 \cdot 10^{7}$ A (see early estimation).

The energy loss in needle is

$$E = I^2 Rt = (3 \cdot 10^7)^2 2.2 \cdot 10^{-5} 6.75 \cdot 10^{-8} = 1.33\,kJ\ .$$

The water requests 2269 kJ/kg for evaporation.Consequently, we need 0.6 gram/Hz of water for cooling of a needle edge in every cartridge.

8. Cost of the thermonuclear fuel.

Deuterium. The sea water contains deuterium about $1.55 \cdot 10^{-4}$ %. The World produces about tens thousand tons in year. Cost 1 $/g.

Tritium. The special nuclear reactors can produced it. Now the cost is 30,000 $/g. In future an expected cost will be from 100K÷200K $/g.

Helium-3. Very rare isotope. The Helium-4 contains $1.3 \cdot 10^{-6}/1$ of the Helium-3. Cost is 30K $/g. One project offers to extract it on Moon and delivery to Earth.

Lithium 6 -7. Nature mixture cost 150 $/kg.

Uranium-238 contains 0.7% of Uranium-235. It cost 90÷250 $/kg.

Plutonium-239. Cost 5600 $/g.

As you see the thermonuclear fuel D+D is the cheapest, but D+T has the lowest temperature for thermonuclear reaction. All the current experimental thermonuclear installations are using the D+T. Look your attention, the offered method allow to get very high thermonuclear temperature. We take U = 15 kV, but no limit take U = 50,100, 200 kV. The 200 kV produce the temperature $T = 200 \cdot 10^{3} \cdot 1.18 \cdot 10^{4} = 2.36 \cdot 10^{9}$ K (two billions!). As you see in fig. 4 and estimations over, that significantly increase the probability of thermonuclear reaction and produce a fuel for the other reactor**.**We can use the cheap fuel produced small neutrons, large protons, expensive elements, which can be a fuel for thermonuclear reactors.

Below in Table 7 theproperties of some material suitable for the offer installation**.**

Table 7. Properties of some material suitable for the offer installation**.**

Material	Tensile strength kg/mm^2	Density g/cm^3	Fibers	Tensile strength kg/mm^2	Density g/cm^3
Steel A514	76	7.8	S-Glass	471	2.48
Aluminum alloy	45.5	2.7	Basalt fiber	484	2.7
Titanium alloy	90	4.51	Carbon fiber	565	1,75
Steel Piano wire	220-248	7.8	Carbon nanotubes	6200	1.34

Issue: [7] p.370.

Discussion

About sixty years ago, scientists conducted Research and Development of a thermonuclear reactor that promised then a true revolution in the energy industry and, especially, in humankind’s aerospace activities. Using such reactor, aircraft could undertake flights of very long distance and for extended periods and that, of course, decreases a significant cost of aerial transportation, allowing the saving of ever-more expensive imported oil-based fuels. (As of mid-2006, the USA DoD has a program to make aircraft fuel from domestic natural gas sources). The pressure, time and temperature required for any particular fuel to fuse is known as the Lawson criterion L. Lawson criterion relates to plasma production temperature, plasma density and time. The thermonuclear reaction is realized when L is more certain magnitude. There are two main methods of nuclear fusion: inertial confinement fusion (ICF) and magnetic confinement fusion (MCF).

Existing thermonuclear reactors are very complex, expensive, large, and heavy. They cost many billions of US dollars and require many years for their design, construction and prototype testing. They cannot stably achieve the nuclear ignition and the Lawson criterion. In future, they will have a lot of difficulties with acceptable cost of nuclear energy, with converting the nuclear energy to conventional energy, with small thermonuclear installation suitable for transportation or space exploration. Scientists promise an industrial application of thermonuclear energy after 10 – 15 years additional researches and new billions of US dollars in the future. But old methods do not allow us to reach an industrial or transport engine in nearest future.

In inertial confinement many scientists thought that short pressure (10^{-9} – 10^{-12} s), which they can reach by laser beam, compress the fuel capsule, but this short pressure only create the shock wave which produced the not large pressure and temperature in a limited range area in center of fuel capsule. The scientists try to reach it by increasing NIF, but plasma from initial vaporization the cover of fuel capsule does not allow to delivery big energy. After laser beam, the fuel capsule is "naked" capsule. Capsule cannot to keep the high-energy particles of the nuclear ignition and loss them. Producing the power laser beam is very expensive and has very low efficiency (1 - 1.5%).

The offer method does not have these disadvantages. One directly heats and presses fully the fuel to high temperature and pressureby electric impulse. In Versions 1, 3 one protects the fuel by the heavy elements having high number of nucleons A and charges Z. They reflect the light protons, D, T, repels high-energy reacted particles (^{4}He, p) back to fuel and significantly increasing the conformation time.

The electric cumulative idea cannot be used for thermonuclear reaction in its classical form. Produced pressure and temperature by laser ICF and magnetic MCF are not enough for thermonuclear reaction. The main author innovation is using the rocket electric explosive for acceleration very small fuel for very high speed (from 0 km/s up 1000 km/s and more), That increases the kinetic energy (temperature) of the fuel in hundreds times.

Author noted that the mass of fuel is very small and allows reaching the high speed of pressing by high intensity electric field.

The impotent innovations are the compressed the fuel gas into fuel cartridge at room temperature and an electric impulse for heating of fuel up the thermonuclear temperatures. The current ICF uses the frozen fuel about absolute zero. That is not acceptable for practice. Author also suggested the transport nuclear engine and nuclear rocket.

The method possible allows to use reaction D+D (instead D+T) with cheap nuclear fuel D (Tritium is very expensive – about 30,000 USD per 1 g, deuterium costs 1 $/g). One also allows using the compressed fuel-gas at room temperature.

Conclusion

The author offers a new small cheap electric cumulative and impulse inertial thermonuclear reactors, which increases the pressure and temperature of a nuclear fuel in thousands times, reaches the ignition and full thermonuclear reaction. Electric Cumulative and Impulse AB Reactor, herein offered by its originator, contains several innovations and inventions.

Main of them is using a electric explosive, which allows to accelerate the thermonuclear fuel to very high speed (up and more than 1000 km/s) which (as it is shown by computations) compresses the fuel in million times and heating up the hundreds million degrees of temperature. The second main innovation is the additional heating the fuel by electric impulse to up temperature in 15keV and more (hundreds millions of degrees). Important innovation is compressed gas fuel at room temperature, instellation for electric and mechanical energy and thermonuclear rocket.

The offered reactor is small, cheap, may be used for cheap electricity, as engine for Earth transportation (train, truck, sea-going ships, aircraft), for space apparatus and for producing small and cheap and powerful weapons. Closed ideas are in [1]-[10].

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Alexander A. Bolonkin was born in the former USSR. He holds doctoral degree in aviation engineering from Moscow Aviation Institute and a post-doctoral degree in aerospace engineering from Leningrad Polytechnic University. He has held the positions of senior engineer in the Antonov Aircraft Design Company and Chairman of the Reliability Department in the Clushko Rocket Design Company. He has also lectured at the Moscow Aviation Universities. Following his arrival in the United States in 1988, he lectured at the New Jersey Institute of Technology and worked as a Senior Scientist at NASA and the US Air Force Research Laboratories.

Bolonkin is the author of more than 250 scientific articles and books and has 17 inventions to his credit. His most notable books include The Development of Soviet Rocket Engines (Delphic Ass., Inc., Washington , 1991); Non-Rocket Space Launch and Flight (Elsevier, 2006); New Concepts, Ideas, Innovation in Aerospace, Technology and Human Life (USA, NOVA, 2007); Macro-Projects: Environment and Technology (NOVA, 2008); Human Immortality and Electronic Civilization, 3-rd Edition, (Lulu, 2007; Publish America, 2010):Life and Science. Lambert Academic Publishing, Germany, 2011, 205 pgs. ISBN: 978-3-8473-0839-3. http://www.archive.org/details/Life.Science.Future.biographyNotesResearchesAndInnovations; Femtotechnology and Revolutionary {rojectsts, Lambert, 2011, p.530; New Methods of Optimization and their Application, Moscow High Technical University named Bauman (in Russian: Новыеметодыоптимизацииихприменение. МВТУим. Баумана, 1972г., 220 стр). List and linksof Bolonkin's publication: http://viXra.org/abs/1604.0304.Homepage: http://Bolonkin.narod.ru.