Article6 Tritium Fusion mistake after Zarek 9 16 16

Cost of Tritium Fusion Energy

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Abstract

For the past sixty years, scientists have spent approximately one hundred billion dollars in an attempt to develop tritium thermonuclear energy. They were unsuccessful. No stable thermonuclear reactions were achieved. Current plans are to design an expensive, but workable industrial installation. It will cost tens of billions of US dollars and will possibly only begin to produce electric energy 15 – 20 years from now. Even if the new designs were viable, they are economically unfeasible. Currently, Tritium is used for fusion ignition because the tritium-deuterium thermonuclear reaction (T+D) has the lowest ignition temperature (≈100 million degree) in contrast to deuterium thermonuclear reaction (D+D) which has a fusion ignition temperature 50 - 100 times hotter. This paper demonstrates that because tritium fuel is very expensive ($30,000/gram and more), the electricity generated by the tritium thermonuclear reactor will cost (≈ $1/kwh), at least 10 times more than conventional sources of energy (≈ $0.1/kwh, 2015). Even using Li-6, Li-7 blankets to breed tritium from fusion reactions cannot be a full solution, because, as we will show, they can only restore a maximum of 30% of the expensive tritium fuel. Hundreds of billions of dollars were spent in vain over the past sixty years for R&D of tritium fusion. It is the costliest mistake in the history of science! Research and Development (R&D) of huge, very expensive tritium fusion installations should be abandoned and in its stead, develop viable and economically feasible, inexpensive, small reactors that use deuterium fuel and high temperatures. That decreases the fuel cost by 30,000 times. Viable designs of small thermonuclear reactors have been offered by senior author in [8,9] where an analysis of the problems with the various configurations of the new small and cheap fusion reactors are detailed therein.

Keywords*: Cost of* th*ermonuclear fuel, Cost of thermonuclear energy, Cost of thermonuclear reactor.*

INTRODUCTION

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 aerospace. Using such reactor, aircraft could undertake flights of very long distance and extended periods of time significantly decreasing the cost of aerial transportation, freeing us from the reliance on ever-more expensive imported oil-based fuels.

Unfortunately, this task is not as 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. Tritium, however, is very expensive.

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. In order for a reactor to be viable it must be able to reach *ignition* stage, that is, when 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. The conditions needed for a nuclear fusion reactor to reach *ignition* stage is the "triple product" of density, confinement time, and plasma temperature T. 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 key to practical fusion power is to select a fuel that requires the minimum amount of energy to fuse, 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. For the D-T reaction, the physical value is about $L = nT\tau > (10^{20} - 10^{21})$ 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]. The thermonuclear reaction of $^2H + {}^3D$ realizes if $L > 10^{20}$ in CI (meter, kilogram, second) units. This number has not yet been achieved in any fusion reactor.

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

In inertial confinement laser 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 the 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 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 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, the most popular designs being tokamaks and stellarators.

Short history of ICF thermonuclear fusion. 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. Although net energy can be released even without ignition (the breakeven point), ignition is considered necessary for a *practical* power system. The resulting design, the National Ignition Facility (NIF), commenced construction at LLNL in the early 1990s, was six years behind schedule and over-budget by some $3.5 billion. Like earlier experiments, NIF failed to reach ignition and is, as of 2015, 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 "fast ignition" laser facility 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. Basic data on a few of the current inertial laser installations:

1. NOVA uses laser NIF (USA), has 192 beams, impulse energy up 120 kJ. Can reach density of 20 g/cm^3, speed of cover is over 300 km/s. NIF has failed to reach ignition and is, as of 2013, generating about 1/3rd of the required energy levels. NIF cost is about $3.5B.
2. YiPER (EU) has impulse energy of 70 kJ.

2. OMEGA (USA) has impulse energy of 60 kJ.
3. Gekko-XII (Japan) has impulse energy of 20 kJ. Can reach density of 120 g/cm^3.
4. Febus (France) has impulse energy of 20 kJ.
5. Iskra-5 (Russia) has impulse energy of 30 kJ.

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.

The most well-known project of magnetic fusion is ITER. **ITER** (International Thermonuclear Experimental Reactor) is an international nuclear fusion research and engineering mega project, which will be the world's largest magnetic confinement plasma physics experiment. Construction of the ITER Tokamak complex started in 2013 and the building costs are now over US$14 billion as of June 2015. ITER began in 1985 as a Reagan–Gorbachev initiative and expected completion is in 2027. ITER reactor alone requires about one billion annually.

Similar projects. Other planned and proposed fusion reactors include DEMO, Wendelstein 7-X, NIF, HiPER, and MAST, as well as CFETR (China Fusion Engineering Test Reactor), a 200 MW tokamak.

Cost of Tritium Thermonuclear Energy.

Cost. The lowest fuel ignition temperature for thermonuclear reaction is a mixture (ratio of weight 60%+40%) of tritium + deuterium (T+D). This temperature is tens of millions of degrees but it is still easier to attain than other possible fuels (for example D+D) which have ignition temperatures 50 - 100 times hotter than T+D fuel.

All present thermonuclear installations use tritium (T+D) fuel but they cannot reach the required temperature.

Tritium is very expensive: Currently it costs $30,000/gram [1]!

Deuterium is produced from seawater. It is cheap: Currently it costs about $1/gram.

Let us estimate the cost of energy produced from one milligram tritium (10^{-6} kg). As the cost of deuterium is negligible, it is insignificant for these computations. The estimation is very simple. We will give a detailed computation that will make it easy to understand.

Thermonuclear energy of two nuclei T+D is $E_1 = 17.6$ MeV $= 17.6 \cdot 10^{6} \cdot 1.6 \cdot 10^{-19} = 2.8 \cdot 10^{-12}$ J .

$$T + D \rightarrow {}^4He\ (3.5\ MeV) + n\ (12.1\ MeV). \qquad (1)$$

One milligram of T contains this many nuclei:

$$N = \frac{M}{\mu m_p} = \frac{10^{-6}}{3 \cdot 1.6 \cdot 10^{-27}} = 2.1 \cdot 10^{20} \qquad (2)$$

where $M = 10^{-6}$ kg is mass of one milligram; μ is number of nucleons in nucleus (in T, $\mu = 3$; in D, $\mu = 2$); $m_p = 1.6 \cdot 10^{-27}$kg is the mass of one nucleon.

Helium energy ^{4}He (3.5 MeV) from (1) is easy to convert to heat. However, it is only 3.5/17.6 = 20% of the total nuclear energy. The neutron energy *n* (12.1 MeV) is difficult to harness, because the neutron has large penetration ability (tens of cm) and reacts with matter producing harmful radioactive isotopes.

The reaction probability is characterized by the cross section. Typical thermonuclear cross sections of main fuel particles are shown in fig.1.

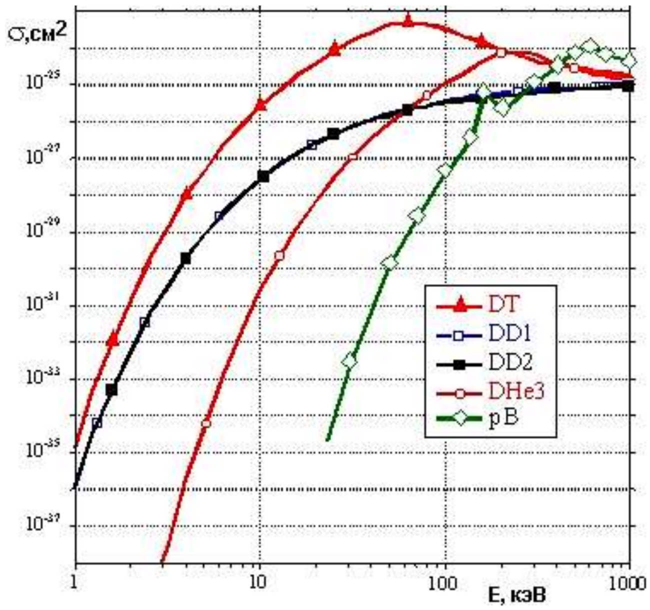

Fig.1. Thermonuclear cross section reaction of D+T, D+D (1), D+D (2), D+^{3}He, and p+B vs kinetic energy E [Kev] of the particles.

The conventional heat engine has the efficiency coefficient of about η = 0.3. The total efficiency coefficient may be as low as 0.2·0.3 = 0.06. We will take the reactor efficiency η = 0.2. The total thermonuclear energy of one milligram of tritium is

$$E = E_1 N\eta = 2.8\cdot10^{-12}2.1\cdot10^{20}0.2 = 1.2\cdot10^8\,J, \qquad (3)$$

One kilowatt-hour has the energy E_h= 10^3·3600 =3.6·10^6 W/h. Therefore, one milligram of tritium with the proper T+D ratio gives

$$C = \frac{E}{E_h} = \frac{1.2\cdot10^8}{3.6\cdot10^6} = 33.3 \text{ kwh} \qquad (4)$$

Using current cost of \$30,000/gram, one milligram of T costs \$30 so we get 33.3 kwh of tritium thermonuclear energy. One kwh will cost

$$c = \frac{30}{33.3} = 0.9 \text{ dollars/kwh} \qquad (5)$$

Currently, electric energy costs about 9 cents/kwh. That is the average price from conventional sources (gas, oil, water, wind, solar: 4÷14 cents/kwh, see [8] - [9]).

Value (5) is 10 times MORE than the current cost of energy. What did the best nuclear scientists who spent billions of dollars over tens of years accomplish? To get energy that is ten times more expensive than the present? And in addition, assuming that all of the above is free, you have to deal with the problems of radioactive waste and security. And even if we breed tritium with lithium blankets, we will show that the cost of tritium energy will still be **three-four** times more than the cost of current non-nuclear energy.

But is it possible that in the future the cost of tritium will decrease? Researchers predict the cost of tritium will increase. Currently tritium is produced in nuclear reactors as a by-product and its customers are mostly the thermonuclear research laboratories. It is very expensive. Now tritium costs \$30,000/gram [1]! In the future, it is expected to cost \$84,000÷130,000/g (400,000 ÷ 1,900,000 \$/g, 2033) [2]. That increase in price inexorably raises the cost (5) of tritium energy by several times. It will not be acceptable as a viable power source. The only hope for a lower cost would be that a dedicated tritium production technology emerges that makes tritium at a cheaper cost than the present. The default, however, is that price will rise.

Note, we estimated only part of the full cost of tritium fusion energy, namely the cost of fuel. Gigantic thermonuclear installations, employing highly qualified staff, and additional required R&D further increase the cost of electricity produced by tritium.

Presently tritium is produced mainly from heavy water moderators in nuclear reactor. Processing several thousand tons of heavy water to extract only a few kg of tritium. Scientists working with current tritium reactors argue that Tritium fusion facilities will be able to produce more tritium than it consumes by means of lithium breeder blankets. Thus, the cost of tritium will decrease.

Upon closer scrutiny, however, this argument fails. We will subsequently consider neutron loss. But even assuming negligible loss, tritium reactors produces high energy neutrons. Capturing these neutrons requires a very thick lithium blanket. Also, the consumption of nuclear fuel is very small. Both of these factors makes the concentration of tritium in lithium very small on the order of some kg Thisonly increases the cost of its extraction and overall raises the price of tritium.
We will consider breeder blankets in more detail below.

Detailed consideration of tritium production in ICF

Possible candidates for fusion fuel include deuterium (D, ^{2}H) and tritium (T, ^{3}H) as well as helium-3 (^{3}He). These are not the only candidates, many other elements can also be fused together, but the larger electrical charge of their nuclei requires a much higher temperature for ignition. Only the fusion of the lightest elements is seriously considered as a future energy source. Although the energy density of fusion fuel is even higher than that of fission fuel, and fusion reactions sustained for a few minutes have been achieved, utilizing fusion fuel as a net energy source remains only a theoretical possibility.
The easiest nuclear reaction which requires the lowest energy, is (1). This reaction is common in research, industrial and military applications, usually as a convenient source of neutrons. Deuterium is a naturally occurring isotope of hydrogen and is commonly available. The large mass ratio of the hydrogen isotopes makes their separation easy compared to the difficult uranium enrichment process. Tritium is a natural isotope of hydrogen, but because it has a short half-life of 12.32 years, it is hard to find, store, produce, and is expensive. Consequently, the deuterium-tritium fuel cycle requires the breeding of tritium from lithium using one or two of the reactions (6) (we will show that the second reaction is uncommon):

$$n + {}^6\mathrm{Li} \rightarrow {}^4\mathrm{He}\ (1.92\ \mathrm{MeV}) + \mathrm{T}\ (2.58\ \mathrm{MeV})\ , \quad n\ (>2.5\ \mathrm{MeV}) + {}^7\mathrm{Li} = {}^4\mathrm{He} + \mathrm{T} + n'. \quad (6)$$

The reactant neutron is supplied by the D-T fusion reaction shown above (1), and the one that has the greatest yield of energy. The reaction with ^{6}Li is exothermic, providing a small energy gain for the reactor. The reaction with ^{7}Li is endothermic and though it does not consume the neutron. In order to have any type of gain in neutron production at least some ^{7}Li reactions must take place to replace the neutrons lost to absorption by other elements. Most reactor designs use the naturally occurring mix of lithium isotopes.

Several drawbacks are commonly attributed to D-T fusion power:

1. It produces substantial amounts of neutrons that result in the neutron activation of the reactor materials.
2. Only about 20% of the fusion energy yield appears in the form of charged particles with the remainder carried off by neutrons, which limits the extent to which direct energy conversion techniques might be applied.
3. It requires the handling of the radioisotope tritium. Similar to hydrogen, tritium is difficult to contain and may leak from reactors in some quantity. Some estimates suggest that this would represent a fairly large environmental release of radioactivity.

The neutron flux expected in a commercial D-T fusion reactor is about 100 times that of current fission power reactors. This poses great problems for material design. To illustrate this point, after a series of D-T tests at JET, the vacuum vessel was sufficiently radioactive that remote handling was required for the year following the tests.

Production and demand of tritium.

According to the 1996 report from the Institute for Energy and Environmental Research, only 225 kg (496 lb.) of tritium has been produced in the United States since 1955. At the time of the report, only about 75 kg (165 lb.) remained due to its continual decay into helium-3.

Special heavy water reactors at the Savannah River Site produced tritium for American nuclear weapons until their closures in 1988. With the Strategic Arms Reduction Treaty (START) after the end of the Cold War, the existing supplies were sufficient for the smaller stockpile of nuclear weapons for some time.

The production of tritium was resumed with lithium irradiation rods at the reactors of the commercial Watts Bar Nuclear Generating Station in 2003–2005 followed by extraction of tritium from the rods at the new Tritium Extraction Facility at the Savannah River Site beginning in November 2006.

Canada has 21 heavy water reactors (CANDU reactors) that produce significant amounts of tritium (2.5-3.5 kg) for civilian applications and is the only source of non-military tritium.Tritium is produced in heavy water-moderated reactors whenever a deuterium nucleus captures a neutron. This reaction has a quite small absorption cross section, making heavy water a good neutron moderator, and relatively little tritium is produced. Even so, cleaning tritium from the moderator may be desirable after several years to reduce the risk of its escaping into the environment. The company Ontario Power Generation formerly known as "Ontario Hydro" in Darlington commissioned a **Tritium Removal Facility (TRF)** for the isolation of the isotope from the heavy water moderators. This facility chemically extracts tritium from the moderator water of all of Ontario Power Generation's CANDU reactors, using a two-stage process. Stage 1 is a *vapor phase catalytic extraction (VPCE) process* which extracts the tritium in vapor form. Stage 2 is a *cryogenic distillation process* which then distills the tritium at low temperatures and immobilizes it.They can process up to 2,500 tons of heavy water a year, and separate out about 2.5 kg (5.5 lb.) of tritium, with a purity greater than 98%, making it available for other uses. The CANDU are mostly scheduled to retire around the year 2025.

Large amounts of tritium are required for experiments and testing of thermonuclear power facilities. For example, to run ITER will require a minimum of about 3 kg of tritium. The start of the DEMO will need 4 -10 kg. Hypothetical tritium reactor would consume **56** kg of tritium to produce 1 GW of electricity per year, while global stocks of tritium for 2003 were a total of 18 kg.

Estimation of the tritium production by T+D ICR reactors.

Some scientists think: T+D Reactors are capable of producing more tritium than they consume. They show thereactions:

$n + {}^{6}Li \rightarrow {}^{4}He$ (1.92 MeV) + T (2.58 MeV), n (>2.5 MeV) + $^{7}Li = {}^{4}He + T + n'$. (6)'

Cross sections of thesereactions are in fig.2.

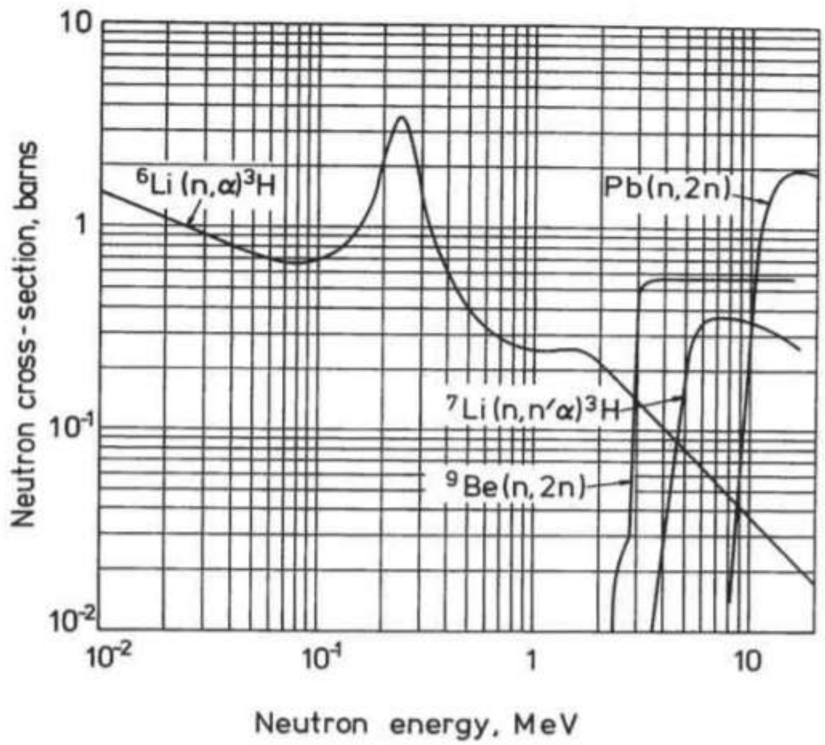

Fig.2. Cross section for reaction $^{6}Li(n,\alpha)^{3}H$, $^{7}Li(n,n\alpha)^{3}H$, $^{9}Be(n,2n)$, Pb(n,2n). Other important cross sections include elastic and inelastic scattering cross sections for Li, Be, Pb, needed for the slowing down (moderation) of the 14 MeV primary neutrons and neutron absorption cross sections for structural material (Figure from M. Sawan).

Let us consider this suggestion in more detail.
Tritium production by T+D reactor may be represented by the equation:

$$\eta = \sum_{i=1}^{i=6} \eta_i \ . \tag{7}$$

Where η is the relative remainder of the total neutrons after loss (which dictates the amount of tritium able to be produced);η_i is the remainder in local stages (regions).

But before we estimate the losses in each of the stages we will show the impossibility of achieving $\eta > 1$ by showing the unlikeliness of the second reaction in (6). Let us consider the ideal case where there is no loss except from collisions of neutrons with other particles. The average neutron loses most of its energy in scattering (elastic collisions which converts its kinetic energy to heat) BEFORE making any useful inelastic absorptioncollisions (the second equation in (6)).

Number of collisions the moving neutron has with the surrounding motionless particles for a given loss of energy is (see Kikoin [10], p. 924):

$$\xi = 1 + \frac{(A-1)^2}{2A} \ln \frac{A-1}{A+1}, \quad N = \frac{1}{\xi} Ln \frac{E_2}{E_1}, \tag{8}$$

Where$N$is number of collisions; A is nuclear number of motionless particle; E_1 is the initial energy of neutron, MeV; E_2 is the final energy of the neutron, MeV.

For ^{7}Li the value $A = 7$, maximum $E_2 = 14.1$ MeV, minimum $E_1 = 2.5$ MeV. So $N = 6.65$.

Let us estimate the probability of an absorption collision with Li-7. For E = 5 MeV the cross section of neutron scattering by Li-7 and Li-6 is about $\sigma \approx 1$ barn (1 barn = 10^{-24} cm^2) [10] p.904. For Li-7 absorption $\sigma = 0.15$ barn. Consequently, free paths$l = 1/n\sigma$ before a scattering collision is 19 cm, before an absorptioncollision with the 50% Li-7 the free paths is 292 cm. Before colliding with Li-7 the neutron has $N_s = 292/19 \approx 15$ scattering collisions with Li before an absorption collision with Li-7 and has already lost enough kinetic energy that it is below the required minimum of 2.5 MeV. That means that the probability of a reaction with Li-7 is close to zero (1/15) and $\eta < 1$. We will show that it is closer to$\eta \approx 0.31$.This shows how the breeder reactors possessing$\eta > 1$is not possible even though all of them produce additional neutrons from the first reaction in (6).

As for the neutron n' produced in the second equation of (6), it is possible to show that its energy will be $E = 1.45$ MeV and cannot take part in a reaction with Li-7.

Let us now give a detailed estimate of the losses in the$\eta_i$main stages(fig.3):

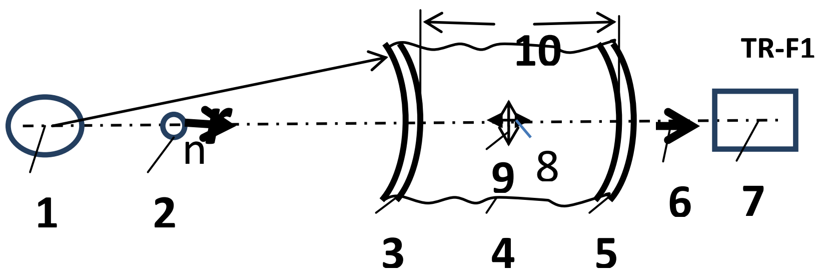

Fig.3. Loss of tritium in breeder production in T+D nuclear ICF reactor. *Notations*: 1 –nuclear reaction zone; 2 – neutron produced from reaction (1); 3 – strong spherical wall that can containthe very high nuclear pressure and temperature; 4 – layer (zone, area, mixture) of the Li-6 and Li-7 “blanket” (used as retardant, tritium manufacturer, heat transfer agent); 5 – outer spherical wall (possible neutron reflector); 6 - moving mixture 4 totritium extraction factory (once per 2 – 3 years); 7 – tritium extraction factory (plant); 8 – slow neutrons moving in radial direction; 9 - slow neutrons moving perpendicular to the radius; 10 – thickness δ of mixture 4.

1) η_1 is the percentage of fuel that is actually fused during the thermonuclear reaction. Reaction speed is linearly dependent on density of the fuel components. Reaction speed decreases when fuel density decreases and practically stops when the plasma has considerably expanded. The combustion time of ICF reactor is very small (about 10^{-7} s). All of the tritium cannot undergo combustionduring this short time and some tritium is lost by incomplete combustion. We take $\eta_1 \approx 0.7$ (70% combustion).

2) $\eta_2$is the fraction of neutrons that managed to get past sturdy wall 3. This strong, thick wall must contain the high pressure and temperature of the small nuclear explosion. The wall absorbs part of the neutrons and producesradioactive isotopes. These harmful isotopes force the replacement of the reactor every 1 – 2 years. The fraction of neutrons not absorbed by wall 3 is $\eta_2 \approx 0.8$.

3) 4 (fig.3) is the area of the Li-6 and Li-7 blanket. The blanket serves a few purposes. It is used as the retardant, the tritium manufacturer and the heat transfer agent. As an example, we consider the mixture50% Li-6 and 50% Li-7 and reactions (6). The second reaction (with Li-7) in (6)requires a neutron with minimum kineticenergy of 2.5 MeV. That means thatif the remainder of the neutron’s kineticenergy after its dissipation collisions is lower than 2.5 MeV, this reaction cannot be initiated and the energy is used to heat the lithium.

We use thefollowing data for our estimation:

Li-6. If neutron has energy E=10 MeV, Li-6 cross section area is $\sigma = 2.5 \cdot 10^{-2}$ barns (1 barn = 10^{-24}cm^2) (Fig. 2), and mileage (free path) $l = 1/n\sigma = 750$ cm (here mixture density $n = 5.33 \cdot 10^{22}$ 1/cm^3). This mileage is very big and the layer 10 must be very large. That means, we must use the mix in with the Li-6 an efficient retardant or have a very thick blanket. If $E \approx 0$, the Li-6 cross section is huge with$\sigma \approx 940$ barns, mileage of neutron$l = 0.02$ cm which makes it an efficient retardant.

Li-7. If neutron has energy E=10 MeV, Li-7 cross section area is $\sigma = 3.5.10^{-1}$ barns and mileage $l = 73$ cm. If $E \approx 0$, then$\sigma \approx 0$ barns because the reaction cannot occur since the neutron lacks the required energy.

Ratio of remaining neutrons is $\eta_3 \approx 1$ with no gain.
Cost of lithium is 270 $/kg (2015).

4) Let us estimate the neutrons leak through walls 3, 5. Assume that only wall 5 has the neutron reflector with albedo $a = 0.5$ (wall 3 cannot have reflector), for neutron 2 from 6 directions we get the coefficient of neutron leak from zone 4:

$$\eta_4 = 1 - \left[\frac{1}{6} + \frac{1}{6}(1-a)\right] = 0.75 \ . \qquad (9)$$

The cost of a beryllium reflector is 4480 $/kg.
5) The loss of tritium in decay. The lithium blanket is located in the reactor for a minimum of two years. Tritium half-life is 12.3 years. That means the average remainder coefficient is about η_5 =1 - 1/12.3 = 0.92.

6) The loss of tritium in extraction. Tritium extraction is a specialized technology and a very expensive manufacturing process. But even at best we cannot hope to make a full tritium extraction. A realistic extraction coefficient is about η_6 = 0.9.

The result, we get the relative tritium (after more than two years) according to (7):

$$\eta = \eta_1\eta_2\eta_3\eta_4\ddot{}\eta_5\eta_6 = 0.7\cdot0.8\cdot1\cdot0.75\cdot0.92\cdot0.9 \approx 0.35 < 1. \qquad (10)$$

That means we can only restore 1/3of initial amount of tritium and its cost will be about current price.

In 2011, the US Department of Energy (DOE) after expending billions of dollars for R&D of nuclear energy financed the JASON organization to estimatewhether tritium reproduction of η= 1 is feasible. In report [3] (without authors??) JASON wrote that the correct installation (reactor) can haveη = 1.04 ÷ 1.10, i.e. reactor may produce 4 ÷ 10% more tritium then it consumes during 2 ÷ 3 years of operation. In ten years, it would produce an excess in the range of $1.04^{10/2}$= 1.21 to $1.1^{10/2}$ = 1.61, i.e. JASON hopes to get 21% to 61% excess tritium after 10 years of operation. They proposed to buy tritium for 10,000 ÷ 30,000 $/gram and sell it for 100,000 $/gram (?) and concluded that the income of the electric station from tritium production will be 10 times more than the income from electricity. Currently, in order to get1 gram of tritium we must spend 10 times more energy than what we can get from nuclear reaction (1)(T+D → ^{4}He+n).

The JASON estimation is wrong because they do not account for many losses in (10). The detailed analysis shows the probability of reaction ^{7}Li + n + 2.5 MeV → T + 2α + n’ (7) is very small (<1/15).

JASON also suggested that adding trace amounts of^{9}Be or Pbto the lithium can act as neutron multipliers increasing the overall tritium production.This cannot work, however, because their reactions request high negative additional energy of neutron (3 – 10 MeV):

$$n + {}^9Be + 3\ MeV \rightarrow 2\alpha + n' + n'', \quad n + Pb + 10\ MeV \rightarrow Pb + n' + n''. \qquad (11)$$

The energy required for these reactions makes them rareoccurrences. Neutrons lose energy very quickly in scattering collisions and are very soon under the 3 MeVthresholds. The probability of these reactions taking place while the required negative energy is above these values (3 MeV, 10 MeV) is very small. (0.01 – 0.02).

If a fusion station would be designed specially to produce tritium it will lose more energy than is produced since η<1. Furthermore, the extraction of the tritium from the lithium “blanket” requires a specialized factory which consumes more energy than is produced by the obtained tritium. Scientists have been experimenting with tritium since 1960, but cannot get excess tritium (η> 1) by reactions (6).

It may be said that the efficient electric station is abad tritium production plant. The good tritium production plant is an inefficient electric station.
Summary: In reality, the cycles (1), (6) produce much less tritium than it consumes (η<1).

Alternative methods of fusion

Every year about one billion dollars is expended in building ITER, a gigantic installation which will produce very expensive energy tens of times more expensive then what we have now. It is expected to begin to generate electricity in another 10 – 15 years after expenditure of additional tens of billions of dollars. Comparable situations exist in current tritium installations in other countries.

We must stop the profligate fundingof these expensive tritium thermonuclear installations. We must not, however, stop R&D of thermonuclear energy. Our attention and funding must be focused on new ideas and designs using small cheap thermonuclear installations and cheaper fuel. Some designs of these smallthermonuclear reactions are presented in [4-9].

At present in order toreachthe high temperature needed for fusion,scientists use expensive laser pressure (ICF) or heating by an electric currentin one direction(MCF). Theauthor [8] offers using direct fuel heating by means of electric field and opposed fuel jets. That allows to get very high fuel temperature (up to a billion degrees). In articles [4]-[7] the author offers cumulative explosion to attain high-pressure and electric heating necessary for fusion.

Brief information about the current cost of thermonuclear fuel is presented below:

- *Tritium.* Only certain specially designed nuclear reactors can produce it. Presently Tritium cost is 30,000 $/g [1]. In the future, the expected cost will be from 84,000÷130,000 $/g (up to 400,000÷1,900,000 $/g)[2].
- *Deuterium*. Seawater contains deuterium. Mean abundance in ocean water (from VSMOW) 155.76 ± 0.1 ppm (a ratio of 1 part per approximately 6420 parts), that is, about 0.015% of the atoms in a sample (by number, not weight). The World produces tens of thousands of tons in year. Cost 1 $/g.
- *Helium-3*. Very rare isotope currently cheaper than it would be because of natural gas production. Helium-4 contains $1.3*10^{-6}/1$ of the Helium-3. Cost is 30,000 $/g now.
- *Lithium 6 -7*. Natural mixture (Li-7 92%, Li-6 8%) costs 270 $/kg.
- *Boron*. Cost 11,140 $/kg.
- *Beryllium*. Cost 4480 $/kg.
- *Uranium-238* Naturally contains 0.7% of Uranium-235. Natural uranium costs 90÷250 $/kg.
- *Plutonium-239*. Costs 5600 $/g.

As you can see the thermonuclear fuel D+D is the cheapest (by 30,000 times!). Moreover, the reaction D+D produces less and lower energyneutrons. However, D+T has the lowers temperature for thermonuclear reaction/low reactivity.

The required temperature for most of the thermonuclear fuels is around 100 times more than for T+D. That is why it is a popular choice for ignition experiments.

How did it happen that scientific community did not take into account the estimated cost of tritium energy?

Perhaps discussions about the future cost of thermonuclear energy was discouraged via articles not published. Or maybe it was simply assumed that the cost of the thermonuclear energy will be cheap. Perhaps it was assumed that in the future fossil fuel will become prohibitively expensive. Or maybe the assumption is that while expensive today, there would be in the future cheaper ways to produce tritium.

How much cheaper must tritium be to compete with coal? Currently by EIA figures 1 kwh takes about 1.8 cents of coal at $40/ton, To be competitivewith coal Tritium would need to be around 40-45 times cheaper or ~$750 a gram. *Using current cost of $30,000/gram, one milligram of T costs $30 and can produce 33.3 kwh of tritium thermonuclear energy. One kwh will cost*

$$c = \frac{30}{33.3} = 0.9 \text{ dollars/kwh}$$

Even if the cost of Tritium could be cheaper, current approaches are still left with the problem of thermonuclear ignition and the problems which appear in MCF (non-stable of plasma) and laser ICF (uneven compression). The present solution to these problems require gigantic, very expensive installations which provide stable jobs for scientists for many years to come.

But perhaps the approach for thermonuclear ignitions (MCF, laser ICF) was based upon a wrong assumption. Ignition by pressure (very strong magnetic field in MCF or rocket evaporation in laser ICF) have low efficiency and are very expensive methods. The strong magnetic field requires superconductivity and very low temperature. The laser pressure requires powerful lasers with low efficiency. The temperature of the liner increases from shock waves and in time the liner will need replacement along with many other components. To reach the desired temperature and pressure is a very difficult challengewith current technology.

Among the authors new ideas to achievefusion, are new methods to achievehigh temperature. This is a more efficient strategy of increasing the nuclear reactivity. In the temperature range from 10 to 100 million degrees, increasing the temperature by 10 times increases the thermonuclear reactivity by thousands of times. Increasing the pressure (density of nucleus) by ten times increases the thermonuclear reactivity only by ten times.
Temperature significantly increases the probability of thermonuclear reaction and produces fuel that can be used for other reactors**.** We canuse inexpensive fuel to produce small neutrons, large protons, expensive elements, including tritium which can be a fuel for thermonuclear reactors. civil and military industry.

Some of new fusion ideas previously proposed (for example, ultra-cold fusion [6]), are very flexible in the nuclear fuels they can use and are not reliant solely on tritium.

Discussion

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 nuclear ignition and the Lawson criterion. In the future, they will have great difficulty justifying the high cost of nuclear energy, the additional cost of converting the nuclear energy to conventional energy, and greater difficulty in designing a small thermonuclear installation suitable for transportation or space exploration. While scientists optimistically promise an industrial application of thermonuclear energy (for T+D) after 10 – 15 years which hinge upon additional research and even morefunding of billions of US dollars in the future, in the near future these old methods will not have any industrial applications nor any feasible transport engine.

Consistent failure to achieve a desired result often requires a paradigm shift, looking at the same thing from a different perspective. The pressure, time and temperature required for any particular fuel to fuse is known as the Lawson criterion *L* (for T+D). Lawson criterion relates to plasma production temperature, plasma density and time. The thermonuclear reaction is realized when *L* is more than a certain magnitude. To achieve this, two main methods of nuclear fusion have been employed: inertial confinement fusion (ICF) and magnetic confinement fusion

(MCF). In inertial confinement, many scientists thought that short pressure ($10^{-9} – 10^{-12}$ s), which they can achieve by laser beam wouldsufficiently compress the fuel capsule, but this short pressure only creates a shock wave which produces insufficient high temperature and pressure to the target area in center of fuel capsule. Scientists tried to reach ignition by increasing laser NIF, but plasma from initial vaporization of the cover of fuel capsule does not deliver sufficient energy. After laser beam, the fuel capsule is essentially a “naked” capsule. Capsule cannot retain the high-energy particles for the duration of the nuclear ignition and loses them. Producing the required quality of laser beam is very expensive and has very low efficiency (1 - 3%).

The main disadvantage of all current reactors is a gigantic cost of installation and using the very expensive T fuel. As it is shown in given research the cost of tritium thermonuclear energy will be at minimum ten times more than current conventional energy. It renders meaningless all current tritium researches and installations.

The pressure strategy cannot be used for thermonuclear reaction in its classical form. The produced pressure and temperature by laser ICF and magnetic MCF are not enough for tritium thermonuclear reaction.

The paradigm that is self-limiting seems to be checkmated in an unsolvable dilemma: Because inertial confinement fusion (ICF) and magnetic confinement fusion (MCF) are the two methods employed does NOT mean that other methods would be just as ineffectual. There are other methods which are published and are all prior art and there must be other methods which have yet not been thought up, but it is these creative solutions that deserve funding.

Alternative methods to trigger fusion have been published by senior author since 1986, methods that can be adaptable for spacecraft propulsion and electricity generation. The simplest and mostperspective method to attain usable fusion energy is by means of a high voltage (70 – 100kV) condenser 100kJ and special fuel capsules containing 0.1mg fuel. [9]. The condensers require no special material and can be made from aluminum foil and film. Author is ready to consult with any interested electrical engineer who would like to verify. The important innovations are method for compressing the fuel gas into a fuel cartridge at room temperature and an electric impulse for heating the fuel up to thermonuclear temperatures.

A different butmore complex approach [6] is a new method for achieving thermonuclear reaction using very low temperatures (0.01 ÷ 10K) and high pressure (some thousands or millions of atmospheres). In this method, instead of using the kinetic energy of nucleus against repulsive force of nucleus, (as in all conventional methods under R&D), he uses the blocking of the repulsive forces of nucleus by electrons (the Debye sphere), very low temperature and high pressure. Using today’s technology, it is easier to reach these temperatures and pressures than the hundreds of millions of degrees required by Magnetic or Inertial Confinement. The new method for thermonuclear fusion is very cheap and allows the use of other thermonuclear fuels which are cheaper and can produce the aneutronic reaction. The offered fusion reactor is small in bulk, cheap to construct and operate, may be used for the copious production of very cheap electricity, can be used as an engine for Earth-biosphere transportation (train, truck, sea-going ships, aircraft), for outer space apparatus propulsion and for producing small, cheap and powerful deadly explosive weapons. In brief, the author has offered a comprehensive new Criterion for Ultra Cold Thermonuclear Fusion!

In another innovation by main author [5,7] is the use of rocket electric explosive for acceleration of very small amounts of fuel to very high speeds (from 0 km/s up to 1000 km/s and more), that increases the kinetic energy (temperature) of the fuel by hundreds of times and allows the use of other (not tritium) fuel. Author noted that the mass of fuel is very small allowingto reach the high temperature, speed and pressure required for fusion.

The current ICF uses frozen fuel at close to absolute zero. That is not acceptable for practice. Author also suggested the transport nuclear engine and nuclear rocket.
These methods make possible the use ofD+D reaction (instead D+T) with cheap nuclear fuel D (Tritium is very expensive – about 30,000 USD per 1g, deuterium costs 1 $/g). These methods also allowthe use of compressed fuel-gas at room temperature obviating the requirement for super cooled fuel as is necessary in ICF fusion.

Conclusion

The estimation of tritium reproduction [3] is wrong. Tritium reproduction is a long, very expensive process and yields a maximum of only about 30% from initial. And even if there was an extremely cheap extraction process the price of T+D nuclear electricity would still be 3 – 4 timesmore expensive than it is currently.
Because tritium fuel is very expensive ($30,000/gram and more) the energy produced by a tritium thermonuclear reactor will cost (≈ $1/kwh) which is at least 10 times more expensive than existing sources of energy (≈ $0.1/kwh, 2015), the expenditure of hundreds of billions of dollars and sixty years for R&D of the tritium fusion were spent in vain. It is the costliest mistake in science history. The authors propose abandoning (freezing) R&D of huge very expensive tritium fusion installations and R&D instead cheap small reactors using deuterium fuel and high temperatures which decreases the fuel cost by 30,000 times.

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