Power engineering

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THERMONUCLEAR POWER ENGINEERING: REALITY AND HOPES

V.Ya. Ushakov

Tomsk Polytechnic University
E-mail: rcr@tpu.ru

The basic approaches to realization of thermonuclear synthesis in an operated mode, dynamics of parameter increase of the developed thermonuclear reactors, as well as the role of international cooperation in solution of this problem have been shown. The basic characteristics of the international project ITER are given.

Great hopes in ensuring energy and ecological security are put on development of the new energy sources and new (alternative) means of obtaining electric energy. They may improve drastically the use of substances involved into energy processes and increase considerably the planet resources available for practical use.

Direct conversion of different types of energy into electric one is already widely used in independent energy sources with low power. In recent years powers of these devices have increased so much that in perspective some of them (for example, fuel cells) may find application in great power engineering. The light element synthesis in controlled reaction of thermonuclear synthesis (CTS) which may become practically inexhaustible energy source is still undeveloped for power engineering needs.

Three main reactions:

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

$${}^{3}He + D \rightarrow p + {}^{4}He \qquad (2)$$

$$D + D \rightarrow n + {}^{3}He \qquad (3)$$
$$\rightarrow p + T$$

are considered for being used in power engineering.

Here D and T are the hydrogen isotopes – deuterium and tritium, n, p are the neutrons and protons, respectively, ${}^{3}He$, ${}^{4}He$ are the three- and four charged helium nuclei, i. e. alpha particles.

Neutron, alpha particle and 17,6 MeV energies, 80 % of which fall on neutron, are originated in reaction (1).

Reaction (2) does not give neutrons and further induced radioactivity but it is accompanied by extraction of a great number of energy.

Reaction (3) may occur by two ways: either with extraction of neutron and alpha particle or – proton and tritium.

Reactions (1) and (2) are of the greatest interest. The first one – owing to the greatest number of extracted energy, the second one – due to a simpler solution of the «fuel» problem and absence of the induced radiation.

One of the «fuel» component – deuterium is rather easily available. In the nature deuterium is contained in water: one of each 6700 atoms of hydrogen has a deuterium nuclear. Tritium is radioactive, has a half-life of 12,3 g and therefore, it is absent in large amounts in nature. However, it may be recovered from lithium or its salts if the walls of the reactor vacuum chamber are covered with a shell (blanket) made of them. Neutrons flown out of plasma give the most part of energy for lithium heating at interaction with it but, besides, each of them produces, at an average, atom and a half of tritium. Deuterium – tritium fuel for thermonuclear power plant possesses huge energy content. Tens of kilos of such fuel are enough for providing the whole Russia with energy during the year.

The second problem occurring at implementation of the reaction (1), – the induced radiation – is conditioned by transmutation of nuclei of materials forming the structure of the reactor and its components under the action of fast neutrons. The correct selection of structural materials allows supporting it at safe level.

Reaction (2) is attractive first of all by the fact that a great number (about 500 million tons) of «fuel» – helium-3 (${}^{3}He$) required for it – is on the Moon. There are not more than several hundreds of kilos of it in Earth interior. At the meeting of the RAS Presidium in 2003 the director of the Institute of geochemistry and analytical chemistry named after V.I. Vernadskiy academician E. Galimov said: «...There are serious projects of its (Moon) use in power engineering of the future. ...One of the possible ways of solving the problem (energy shortage – V.U.) is connected with helium-3 application in thermonuclear reaction, its production and delivery from the Moon».

Several countries stated the ambitious plans of mining operation on the Moon, first of helium-3: the USA, Russia, China, India, Japan, European space Agency etc. So, for example, the USA plans to construct on the Moon the industrial plants for producing helium to 2024. The cost of the project is 100 billions of the USA dollars. Nevertheless, specialists consider this project to be not simply profitable, but highly profitable. By 2020 the regular lunar operations at new generation of pilot research ships which exchange shuttles will be resumed. The first moon base is planed to be constructed at the south pole of the Moon which is more preferable from the point of view of solar battery functioning and station energy supply. Spacemen – station constructers – may stay in lunar conditions not more than a week therefore the construction will be carried out by shift work. People and cargos will be regular delivered to the Moon by one more space ship «Orion». After the base construction people can work there till a half of year. NASA management supposes to make the project of moon base international as the ISS. Russia, EU and Japan will be, probably, proposed to participate in the project.

The international law and more definitely – «Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies» stand on the way of the Moon colonization. As for the Moon there are «loop holes» which may be used in order to avoid this Treaty. U.N.O. Subcommittee on peaceful uses of space has to establish order in the Moon legal status and, first of all, close the law loop hole allowing being wildly engaged in private enterprise in space.

So far the physicist efforts are concentrated on engineering implementation of the reaction (1), i.e. on synthesis of deuterium and tritium. Cares for the fuel for (CTS) seem to be a little bit premature when analyzing the problems of its implementation which is worked on by physicians more than 50 years. (Quantity of lithium (~5 kg) produced for today in the world is enough for starting up the thermonuclear reactor [1]). The long-term researches of CTS showed that the development of industrial reactor, as it turned out, is a matter of a rather distant future. In order to overcome natural electric repulsion the nuclei should possess considerable energy. Temperature of deuterium-tritium mixture should achieve, at least, $5\cdot10^7$ K (4,5 keV). Deuterium-tritium mixture in this case represents plasma consisting of positively charged nuclei and electrons. Maintenance of such high temperature in plasma was and is still one of the most important tasks of thermonuclear studying. Plasma is cooled as a result of several processes: electromagnetic energy emission at charged particles collision, «carry over» of heat by the fast neutrons escaping plasma in large quantities, emission, thermal conduction and turbulent convection of plasma articles etc. The reaction may be constantly sustained supplying energy from outside by radiofrequency waves or beams of high-energy neutral particles. However, there is the efficient self-sustained source of supplementary heat – fast α-particles (with energy about 3,5 MeV), which are originated in plasma and give their energy to its particles. These helium nuclei are the «ash» of thermonuclear reactions.

In order to start up the process of self-sustained thermonuclear reactions it is necessary to hold for some time the high-temperature plasma isolated it from the walls. The possible methods of solving this problem are introduced in Fig. 1 [1]. In the Sun and in stars the gravitation holds plasma constantly and therefore, the synthesis reaction occurs there at temperatures (~15 million degrees) much lower than those which should be on Earth.

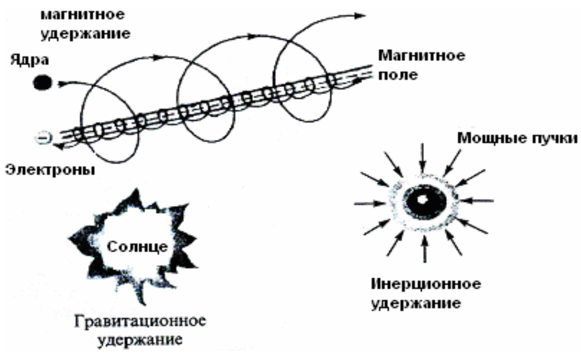

Fig. 1. *Methods of sustaining high-temperature plasma [1]*

Магнитное удержание – Magnetic confinement; Магнитное поле – Magnetic field; Мощные пучки – Powerful beams; Ядра – Nuclei; Электроны – Electrons; Солнце – Sun; Инерционное удержание – Inertial confinement; Гравитационное удержание – Gravitation confinement

Another method is a so-called «inertial confinement». Special target prepared a priori containing fusion fuel of high density, is quickly swaged by ion, laser or X-ray beams for increasing temperature to the critical value, Fig. 2. (One of the similar methods was implemented in hydrogen bomb). Finally, there is one more diagram using magnetic field for plasma thermal insulation which is currently the closest to be implemented in commercial scale. O.A. Lavrentiev the student of the evening secondary school in Sakhalin was the first who proposed in 1945 the principle of plasma thermal insulation by electric field for commercial use of thermonuclear reaction.

1. Reactors with magnetic plasma confinement

Product of time which is necessary for heat to escape plasma (energy confinement time) τ and plasma density n characterizes plasma heat-trapping ability and called the parameter of confinement quality. The product $n\tau$ should be more than $2\cdot10^{20}$ s/m^3 (Lawson criterion), at temperature T=10,0 keV (about 10^8 K) for thermonuclear reactions to self-maintain and give useful energy. Thus, the aim of thermonuclear researches and developments consists in achieving the value of product of three magnitudes: n, τ, T about $2\cdot10^{24}$ s·eV/m^3.

Currently, the ***tokamaks*** – the thermonuclear devices, achieved most of all these conditions. This device proposed by soviet physicists A.D. Sakhorov and I.E. Tamm at the beginning of 1950 got its name from abbreviation of words «TOroidal CAmera with MAgnetic COil». Principles being the basis for this device operation are rather simple, Fig. 2 [2].

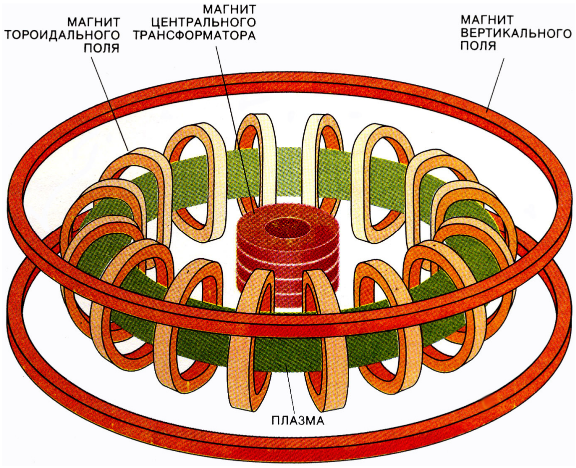

Fig. 2. *Three systems of tokamak magnets [2]*

Магнит тороидального поля – Magnet of toroidal field; Магнит центрального трансформатора – Magnet of central transformer; Магнит вертикального поля – Magnet of vertical field

Plasma is firstly obtained in vacuum chamber having a shape of torus. The system of electric magnets outside the chamber creates the toroidal magnetic field directed along the torus axis. The field acts as a hose which supports pressure inside plasma and prevents its contact with the chamber walls.

Another system of electromagnets in the middle of torus initiates in plasma electric current flowing in toroidal direction. This current heats plasma to about 1 keV. Plasma current creates its magnetic field covering teroid. This field prevents plasma particle drift out of the main area of magnetic confinement. Finally, external conductors generate vertical magnetic field confining plasma filament from up and down, right and left movements inside the chamber.

By the middle of 60-s of the last century soviet physicists headed by academician L.A. Artsimovich in the Institute of atomic energy named after I.V. Kurchatov could obtain such results which persuaded the physicists of other countries in availability of the method of plasma confinement in tokamaks for implementation of controlled thermonuclear synthesis. When they were brought to the notice of international scientific community (the report of I.V. Kurchatov during the visit of government delegation headed by N.S. Khruschev in 1956 to Great Britain) the investigation on controlled thermonuclear synthesis took the international character as the other countries followed the example of the Soviet Union. It turned out that working independently of each other in conditions of strict confidence the scientists of different countries came to the same ideas of realizing the controlled thermonuclear synthesis; at the initial stages the other ideas and diagrams – the idea of so-called stellator proposed by Ya. Spitser in 1951 (plasma filament confinement by external helical magnetic field), the concept of open magnetic trap suggested by academician G.I. Budker and R. Post (1953) were considered. It became obvious that implementation in metal of such seemingly simple idea is conjugated with great difficulties requiring effort integrating. The coordinated actions of the physicists of the advanced countries of the world allowed developing various modifications of tokamak construction which represent large complex devices, Fig. 3.

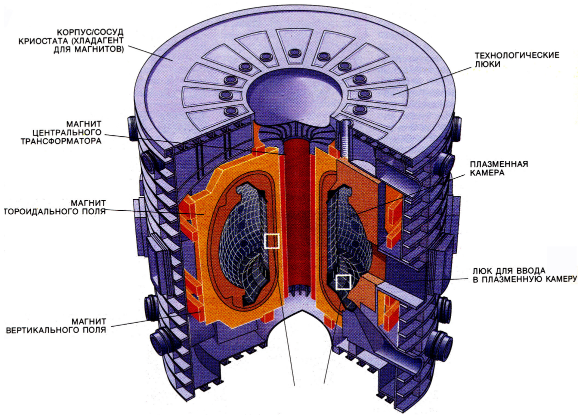

Fig. 3. *The main nodes of tokamak [2]*

Корпус/сосуд криостата (хладагент для магнитов) – Body/reservoir of cryostat (coolant for magnets); Магнит центрального трансформатора – Magnet of central transformer; Магнит троидального поля – Magnet of toroidal field; Магнит вертикального поля – Magnet of vertical field; Технологические люки – Assembly covers; Плазменная камера – Plasma chamber; Люк для ввода в плазменную камеру – Port for entrance into plasma chamber

Today the plasma temperature 30 keV and parameter of confinement quality $2 \cdot 10^{19}$ s/m^3 are achieved in the most powerful test units of this type – tokamak JET (Joint European Torus), tokamak JT-60 in Japan, experimental thermonuclear reactor-tokamak TFTR (Tokamak Fusion Test Reactor) and the device DIII-D in the USA. The product $n\tau T$ during 1970–1990 was increased more than in 100 times, Fig. 4 [1]. This value was redoubled at average each 1,8 year. Beginning from 1970, the power extracted in thermonuclear reactions at various tokamaks increased by 12 orders, Fig. 5.

The main result of works on the problem of controlled thermonuclear synthesis for the first 30 years is the experimental verification of feasibility of plasma confinement with high thermonuclear parameters the most efficient in closed magnetic traps of tokamak type.

Later at tokamaks of various constructions certain record parameters: tokamak JET – ion temperature ($4 \cdot 10^8$ K), and power, exceeding 16 MW, at TORE-SUPRA – confinement time 4,5 min, at JT-60U – thermonuclear yield Q=1,24 were obtained.

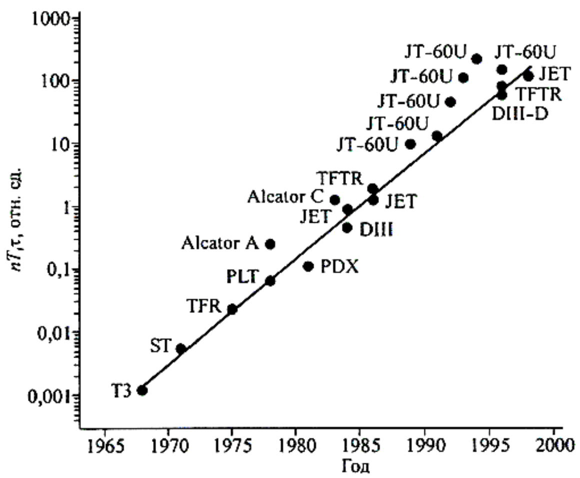

Fig. 4. *Growth rates of triple product nτT [1]*

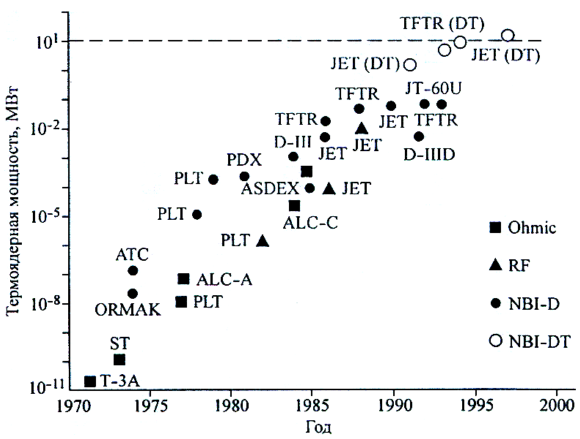

Fig. 5. *Growth of thermonuclear reactor power by years [1]*

In order to do a crucial step to achievement of final aim the international collaboration was put to the qualitatively new level. A new stage of collaboration in solution of the problem of controlled thermonuclear synthesis began in 1985 when during the meeting of two leaders of the USSR and the USA (M.S. Gorbachev and R. Reagan) in Geneva they appealed to collaboration in acquirement of thermonuclear energy «for the good of the humanity». In response to this appeal the engineers and scientists involved into four main programs of studying thermonuclear synthesis carried out in countries of EC, Japan, the USSR and the USA came to agreement to start the collaborative design of the experimental thermonuclear device in 1987. They called it ITER (International Thermonuclear Experimental Reactor); in Russian notation – ITER. Later China and South Korea jointed to them. India and Brazil expressed willingness to take part in the project. The main aims of the ITER project are the achievement of conditions of ignition and long-term thermonuclear burn, which will be typical for real thermonuclear reactor as well as the test and demonstration of technologies for practical use of controlled synthesis.

Reactor ITER will be the largest of all ever built tokamak – its height is 30 m, diameter is 30 m. Plasma volume in the device is 850 m^3; current in plasma is 15 MA, stress of toroidal magnetic field is 5,3 T. The device thermonuclear capacity in various modes 500...900 MW supports during 400 s. In future this time is supposed to be brought to 3000 s that gives an opportunity to carry out the first real researches in physics of thermonuclear burn in plasma at the reactor. Some nodes of this device are shown in section in Fig. 3.

ITER project is rated at more than 20 years and includes three stages: construction (9-10 years), work with hydrogen plasma (5 years), work with tritium (7 years). In 2006 three scientists: Evgeniy Velikhov (Russia), Masadji Ioshikava (Japan) and Robert Aymar (France) were awarded with the prize «Global energy» for the development of scientific and engineering bases of ITER creation.

At the first physical stage the researchers will try to achieve the conditions of ignition and stationary plasma maintenance and conditions for deuterium-tritium synthesis, study the effects of plasma heating by α-particles, dynamics and control of plasma burning as well as diffusion and helium removal when helium bullets gave all energy to plasma. Many technologies: maintenance of superconducting magnets, systems of plasma heating and current maintenance, devices for fuel introduction and «ash» removal, systems of remote service and external supporting systems will be worked at this stage. Technical and engineering problems will be solved, integral parameters and equipment reliability will be determined and alternative materials and constructions will be tested at the long-term engineering stage.

Design and engineering development should result in creation of the reactor which can generate power of 1000 MW owing to deuterium and tritium synthesis at thermonuclear output in three orders of the value more than was achieved at the device JT-60U. ITER is the last but one stage to the way to the practical use of controlled thermonuclear synthesis. Scientific and engineering knowledge obtained in the experiments at ITER should result in construction of demonstration thermonuclear power station in Japan, obviously to 2050 (DEMO project). Its capacity amounts about 1,5 GW; cost of 1 kW·h is about 2 twice higher than now in our country. In perspective the capacity of such stations will increase and cost of energy generated by them will decrease to the level of energy cost of nuclear power plant.

The development engineering project of ITER was completed in 2001 and in 2005 after long negotiations the official representatives of participating countries declared the achievement of agreement about the place of construction of the first demonstrative reactor and transition to project practical realization. The selection is made in favor of French area Kadarash near Marcel where the superconducting tokamak TORE-SUPRA is situated from 1988. The official signing of the agreement about its starting up took place in Paris on the 21 of November, 2006.

In order to provide the safe delivery of bulk and large-size equipment to Kadarash (for example, blocks of channel for plasma confinement are 12×8×8 m, weight

– to 600 tonnes) France engaged to reconstruct and firm the 96 km of route which separate the building site from Marcel – the nearest sea port. 26 bridges will be broadened and firmed and new routes detour the existing tunnels will be equipped. The ITER construction requires about 4,6 billion′, and total cost of the project is 10 billion′. The parts of the participating countries are defined in the following way: European Union – 50 %, the USA, Japan, China, Republic of Korea and Russia – by 10 %. The part of India in 500 mln′ amounts the reserve fund.

Russia participation in ITER project consists in making and delivering the main manufacturing equipment by the agreed list and cash contribution – it forms all together Russian 10% from the total cost of constructing reactor. RRS «Kurchatovskiy institute» will be Russian national center of coordinating all works on ITER. More than 200 Russian organizations participate in the project.

By optimistic forecast the projects ITER and DEMO will be successfully fulfilled and in the second half of this century the contribution of thermonuclear power engineering into the world one will be rather appreciable and to 2100 the capacity of thermonuclear power stations achieve 100 GW.

2. Reactors with inertial plasma confinement

The inertial plasma confinement and respectively, the inertial thermonuclear synthesis (ITS) was proposed in the USSR in the middle of 60-s of the last century. This direction, alternative to a large extent to the first one, is oriented to creation of such conditions (density) at which the main part of thermonuclear fuel «burns off» before the time it flies apart, without efforts for confinement of plasma bunches. In this case, the difficulties which in tokamak consist in plasma confinement were transformed to the task of its heating for a very short time. Time parameters of this process are determined by the blended fuel inertia therefore, heating should be fulfilled by the time of the order 10^{-9} s. Currently the time of producing pulse reactors is at the stage of physical researches and conceptual design substantiation [3]. The efforts of scientists resulted in competition of pulsed «thermonuclear reaction» with magnetic plasma confinement by a number of parameters.

The possibility of creating thermonuclear reactors operating by short pulses at laser and ion beam action depends to a large extent on success in development of lasers and high-current accelerators with high efficiency [4]. It is necessary to increase the efficiency of the warming up lasers to 10...15 % instead of existing 0,3 %, increase pulse frequency to 10–100 explosions per second. These problems refer in full to the beam variant of ITS. In both cases the mechanical and thermal stability of the reactor capable of sustaining the explosions of deuterium-tritium targets repeating for along time with such frequency is rather complex problem. Energy of tens of kW·h is released at explosion of only one target (tablet). Rather high cost of energy which will be generated by ITS-reactors is still the urgent problem [3]. But, nevertheless, at present it is one of the most important directions, it is still developed in Great Britain, France, America, Japan, Russia.

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