IV. RENEWABLE AND ALTERNATIVE ENERGY SOURCES AND BIOFUELS

ARE THE HYBRID NUCLEAR REACTORS THE ANSWER FOR THE FUTURE ENERGY NEEDS?

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Summary Now the chances to get the energy released by the transformation of nuclei (fusion and fission) are significantly larger than they were 10 or 20 years ago due to the development of the hybrid nuclear reactors. They can provide energy with abundant resource, safe, and clean at reasonable cost. The research in nuclear fusion shows that several of the present day plasma devices (both stationary and pulse) have the potential to become the background of a hybrid (fusion-fission) industrial facility for energy production. They will burn the high-level radioactive waste, thus closing the nuclear cycle and will hinder the spread of hazardous materials. A breakthrough in nuclear power is expected in the near future, whichever of the three technologies - fast neutron reactors, accelerators driven systems or fusion-fission hybrid reactors will prove to be the most technologically or economically viable base for hybrid reactors.

Keywords: fusion reactors, fission reactors, synergy, concepts of hybrid nuclear reactors, biology treatment of fission reactor's water.

INTRODUCTION

More than 60 years had passed since beginning of the fusion strive with a main goal – harnessing the energy of the stars. However, this task turned out to be extremely difficult. Now, with ITER, NIF and DEMO we are told that it is necessary to wait 50 years more for the fusion power plant. Indeed the challenges of obtaining “pure” fusion energy are very high, they require considerable efforts, huge investments and time. On the other hand the existing nuclear fission energy sources also have serious problems, hazards and drawbacks. Probably the answer to all these problems are the hybrid fission-fusion reactors, proposed in 1950s by A. Sakharov in Russia and D.Imhoff in USA [1, 2].

Nowadays a resident of the Earth consumes annually 1.8 tons of oil equivalent. This figure is averaged over the entire world population though the spending is quite uneven. At the end of the 21st century the expected consumption can be $40 \div 50$ billion tons of oil equivalent. The number of people on Earth will probably exceed 10 billion. How such a consumption can be provided from gas, oil, coal, or the renewable energy sources? The renewable sources are very good, they should be developed, however they can not provide a high density energy flow which is necessary if we want to have fast trains, highways with charging stations for the electric cars, modern industry with drastic decrease of manual labor, and so on at low CO₂ emission.

This paper is a short review on the principles, experimental devices and projects of fusion-fission nuclear plants which can combine energy production,

production of fuel for the conventional fission reactors and burning of the high radioactive nuclear waste.

FUSION AND FISSION SYSTEMS

The “pure” fusion path to a power plant requires [3]: making modes of “burning plasma”, i.e. switching from heating of the plasma by external sources of energy, to heating it primarily by α particles appearing in the fusion of D and T nuclei; creation of materials for the reactor first wall, enduring neutron fluxes up to 5 MW/m² and radiation defects up to 200 displacements per atom (dpa); operation of the facility for at least 30 years, with short periods for remote maintenance and repair. The problems with the inertial confinement fusion (ICF) are bigger since the plasma parameters of these machines are still far from the parameters achieved by tokamaks and other magnetic confinement fusion (MCF) devices. There are problems with the regeneration of tritium, burned in the fusion chamber, at the subsequent processing of the coolant in order to obtain a closed loop of tritium.

Part of the tasks listed above should be solved by ITER but when and at what cost? The facility will start operation by 2025 and will work for about 25 years. Up to now the expenditures for building ITER will exceed 20 billion euro. According to the initial plans, the results of ITER would allow starting the next step DEMO that should demonstrate successful delivery of fusion energy to the grid. However, at such level of the expenses for ITER, NIF and DEMO (If the latter is going to be build, following the ITER concept) the pure fusion energy has no future.

The present status quo of the fission nuclear energy: The employment of the nuclear fission energy in the middle of 20th century was considered as one big leap in the human society development. However in the dawn of the nuclear “era” Enrico Fermi pointed out that the power production based on thermal fission reactors had no stable future without solving four key problems: (i) abundant supply of raw material; (ii) nuclear safety; (iii) closing the nuclear fuel cycle in the reactor; (iiii) preventing the proliferation of fissile materials. The present day situation adds one more key issue: disposal of the radioactive waste materials produced by the nuclear power stations and the factories producing fuel elements for the fission reactors. Now they are: depleted uranium ~ 1.5 mill tons, spent fuel - 0.4 million tons; water from the first reactor loop - 1 million ton; nuclear waste with smaller activity -10 million ton.

It is clear that all above mentioned problems are still source of serious concerns in the society.

Today about 440 stationary nuclear reactors provide ~ 14% of the energy demand in the world. About 500 smaller reactors are power units of ships and submarines. New reactors are planned or constructed. However the existing nuclear industry will face a shortage of raw material. It is based on fission reaction of the odd isotope U^{235} . The natural uranium contains an average of 0.71% of this isotope. Since many of the uranium ore deposits have natural metal concentration of 0.001 %, the supply of richer ore deposits will be sufficient only until the end of the century. Therefore, if the energy production is going to use the present day technology the price of the fuel elements will rapidly increase. In fact this technology uses less than 1% of the potential of natural uranium. Meanwhile large amount of uranium (the even isotope U^{238}) is kept in warehouses or in costly landfills of high-level activity nuclear waste. Other negative effects of the use of current reactor technology for power generation are well known: danger of accidents in the power plants, danger of spreading hazardous materials and nuclear waste (residual actinides, radioactive products of fission and induced radioactivity).

So the answer really could be hybrid reactors (HR). This idea appeared in 1953. The concept was to build a system comprising both fusion and fission of nuclei. In the system center there is a fusion neutron

source (FNS) providing an intensive flux of fast neutrons. In the fusion chamber wall (blanket) the 14.1 MeV neutrons cause fission reactions or transformation of the ^{238}U isotope into plutonium Pu^{239} , (or Th^{232} - in U^{233} , respectively). This concept has been discussed in the initial period of the fusion research (there was such a proposal in a letter written by I. Kurchatov in 1953 to the leaders of the USSR. The idea was given by A. Sakharov). At the same time a California R&D Company in USA made similar proposal to USAEC, (Report LWC-24920) (1953)). Later many prominent scientists actively worked on the issue in the 1970s and 1980s (See for example [4 - 6]. Earlier works are reviewed in [7]). However large systems have not been built both in Russia and USA probably due to insufficient funding.

Further, for about two decades, the interest in the hybrid devices decreased due to the severe accidents at nuclear power plants, the concerns related to spreading of material for nuclear weapons, and last but not least are the economic constraints. But in the last 15 – 20 years quite active scientific and technology studies take place in the field. The development until 2009 is given in the review [3].

The scientific background of the hybrid systems could be inferred from the cross-section curves of the inelastic interactions of fast (DT fusion) neutrons with ~ 14 MeV energy with the uranium U^{238} and thorium Th^{232} nuclei, shown below on Figure 1 and 2. It is seen that the 14 MeV neutron (further – fusion neutron) easily causes fission of the even isotope U^{238} (green line) and gives also birth of secondary new instant neutrons. Left part energy dependence is taken from the [Janis 4] database On the right are specified respective reactions and experimental rate coefficients (reaction rates). These rate coefficients are set for an incident neutron with energy 14.1 MeV. Reaction, referred to as $U^{nnn}(n, f)$ is a radioactive decay (fission) of the relevant isotope. The reaction $U^{238}(n, 3n)U^{236}$ is a threshold conversion of U^{238} to U^{236} with a release of 3 neutrons, the reactions $U^{238}(n, \gamma) Pu^{239}$ shortly denotes a sequence of processes leading to creation of Pu^{239} .

Janis 4. Java-based Nuclear Data Information System <http://www.oecd-neo.org/janis/>,

In the experiment is used a sample of natural uranium metal by 0.71% content of U^{235} .

Fig. 1. Energy dependence of cross-sections for interactions of fast neutrons with the isotope ^{238}U [Janis 4]

The Fig. 1 could also give qualitative idea about differences between hybrid systems and so called fast neutron reactors. These fission reactors use expensive plutonium Pu^{239} (or U^{235}) fuel mixed with uranium U^{238} , so that when in the fission of plutonium are emitted 2-3 fast neutrons – with energy ~ 2 MeV, which are captured by U^{238} nuclei with radiation of gamma quanta, U^{239} is formed, which after 2 consecutive β decays was converted to Pu^{239} . Now one GW breeder reactor is expected to produce about $70 \div 150$ kg of plutonium per year. It should double the amount of fuel in about $10 \div 20$ years. Calculations show that a fusion reactor of similar power would produce $500 \div 900$ kg of plutonium per year (see for example [8]). Such reactor would supply with nuclear fuel 3-4 ordinary nuclear reactor of the same power. It should be inferred from the figure that the fusion neutron give start to much more processes creating new neutrons than one 2 MeV neutron released by the fission of Pu^{239} nucleus.

Reaction	Reaction rate
$^{238}\text{U}(n,2n)\dots^{237}\text{Np}$ ---	0.277 ± 0.008
$^{238}\text{U}(n,3n)^{236}\text{U}$ ----	0.327 ± 0.052
$^{238}\text{U}(n,f)$ -----	1.18 ± 0.06
$^{235}\text{U}(n,f)^*$	0.281 ± 0.017
$^{238}\text{U}(n,\gamma)\dots^{239}\text{Pu}$	4.08 ± 0.24
Neutron leakage	0.41 ± 0.02

The thorium Th^{232} isotope gives much more of these secondary neutrons which can provoke subsequent fission reactions. Comparison of uranium and thorium possible blankets in HR: the energy yield in a natural uranium blanket per one fusion neutron is 8.3 times bigger than in a blanket with thorium. The thorium emits more neutrons by the reaction channels $(n,2n)$, $(n,3n)$. On the other hand, the accumulated in the thorium blanket mass of U^{233} produced after a chain of transmutations is a new fuel for fission reactors. It is much better than the plutonium fuel, which is formed in the uranium blanket. Together with the U^{233} isotope, the formed fuel will contain several percent of U^{232} . This isotope prevents non regulated proliferation of nuclear materials associated with military applications. In addition, working with the isotope U^{233} does not raise the production of hazardous materials. The burning of 90% of the isotope U^{233} in a standard fission reactor reduces the long living nuclear waste. It is a fission reaction with almost no residue.

Fig. 2. Energy dependence of cross-sections for interactions of fast neutrons with the isotope Th^{232}

Reaction	Reaction rate
$^{232}\text{Th}(n,2n)\dots^{232}\text{Pa}$ ---	0.42 ± 0.04
$^{232}\text{Th}(n,3n)^{230}\text{Th}$ ----	0.30 ± 0.05
$^{232}\text{Th}(n,f)$ -----	0.174 ± 0.01
$^{232}\text{Th}(n,\gamma)\dots^{233}\text{U}$	1.63 ± 0.10
Neutron leakage	0.78 ± 0.04

MODERN CONCEPT OF HR

The basic ratio, which a fusion reactor must meet to operate as a generator of energy is as follows:

$$Q_e = G \eta_t M_b > 1 \quad (1)$$

Here Q_e is the overall gain of the energy cycle, G is the power gain in the fusion module, η_t is the thermal efficiency of the power plant, η_d is the driver efficiency, and M_b is multiplication factor of the power in the blanket. At $\eta_t \sim 0.3 \div 0.4$, $\eta_d \sim 0.1$, $M_b \sim 1.2$, the coefficient G should be in the range of 100. If M_b is for example not 1.2 but 10, the gain of the whole energetic cycle Q_e can be the same using a smaller factor G . Therefore, by introduction of a hybrid scheme it is no longer necessary to design a fusion system with such high plasma parameters. A basic requirement for this concept is operation in a slightly subcritical mode:

$$k_{eff} < 0.95 \quad (2)$$

k_{eff} is the effective multiplication factor of neutrons in certain element of the core. It is the average number of secondary neutrons (instant) born in a given particular volume in unit of time per one fusion neutron caught up in the same volume for the same time. We have to take into account that immediately after the first generation of secondary neutrons appears the next generation, then the third generation, etc. In this way for multiplication M_b of the neutron flux in the active core a simple formula for the neutron number is derived [9]:

$$M_b \sim 1/(1 - k_{eff}) \quad (3)$$

Other important coefficient is the "reactivity" ρ of the fission module:

$$\rho = (1 - k_{eff})/k_{eff} \quad (4)$$

More sophisticated calculations [3], taking into account the relative part of the delayed neutrons β_d ,

transmission of neutron channels between FNS and the active core, $T \sim 0.1$, assuming $\rho \sim \beta_d$, and other factors, show that if the fusion reactions power of the FNS, P_f is ~ 1 MW, the thermal power of the whole system P_{th} can be ~ 1 GW.

Before more detailed considerations of the fusion-fission system are given, a few words should be said for the different concepts for transmutation of the actinides.

EXPERIMENTAL SYSTEMS

1. Accelerator technologies

Schemes of particle accelerators producing neutrons are being actively developed recently. In the literature they are known as accelerators driven systems (ADS). Fig. 3 shows the general layout of a nuclear power plant with a hybrid reactor based on this principle. In most projects are considered proton accelerators, creating a continuous flow of particles with energy ~ 1 GeV [10].

The beam of charged particles falls on core composite fuel C-1. As a result of deep splitting of the nuclei herein a neutron source is formed. These neutrons are multiplied by a factor of ~ 29 at the value $k_{eff} = 0.95$ [3]. In zone C-2 the beam is multiplied up to the values $N \sim n_2 \cdot W_{12}$. In this relation $W_{12} \sim 0.4$ is the probability of inducing fission of the active nuclei in the area C-2 by neutrons generated in the zone C-1. If the value of $k_{eff} = 0.95$ the number of the fission acts in zone C-2 by a primary neutron is of the order of $N_f \sim (n_2 / (1 - k_{eff})) W_{12} \sim 100$. Besides the salts composition LiF, MgF₂, MF, (here M denotes minor actinides plus uranium, plutonium and thorium), the zone C-1 contains a neutron absorber such as GdF₃ or SmF₃ that reduces the probability W_{21} of penetration of neutrons from C-2 in C-1.

Fig. 3. Reactor –transmutator

The arrow above shows the direction of the incident beam of accelerated particles. C-1 is the first cascade of the active core with efficient coefficient $k_{1\infty} > 1$; C-2 second cascade – thermal core of transmutation, $k_{1\infty} < 1$; M – actinides; X – sink of thermal neutrons

It is sufficient to add 0.1% Gd in the salt composition to ensure a value of W_{21} of the order of $10^{-3} \div 10^{-2}$, while the quantity of neutrons in area C-1 is decreased by 0.5%. For the traditional scheme based on a subcritical reactor and thermal power of 1 GW, a 50 MW accelerator is required. In the cascade circuit the power of the accelerator can be reduced ~ 10 times and an accelerator of electrons instead of a proton beam can be used. In this case, the accelerator will use 1% of the energy of the reactor instead of 10% which the proton accelerator would draw [3].

2. Fast fission reactors

Fast reactors are nuclear reactors where most of the fission acts are caused by fast neutrons. They contain no neutron moderator and are capable of generating more fissile material than they consume. Important characteristic for the fast reactors is the so called reproductive coefficient (RC). It is the ratio between the produced plutonium Pu^{239} and the burned plutonium and uranium U^{235} . The fast reactors have been investigated for a long time in Russia, Japan, India, France, etc. The biggest facility of the kind exists in the Russian Federation (Beloyarsk, BN - 800). A new 1200 kW machine is

going to be commissioned also in RF. India is planning to build such systems by 2030. Unfortunately, the technology problems of these reactors are quite heavy, besides the installation cost is high and the RC coefficient is not sufficient. The most serious disadvantage is that they produce plutonium which can be used for military purposes. Another drawback is that only high developed “nuclear” countries, having the complete set of technologies for processing irradiated fuel elements (FE) and producing fresh FE can build and use such systems. For these reasons a world-wide commercialization of the fast breeding reactors seems to be impossible. More about these reactors one can find for example in [11].

3. Hybrid fusion-fission systems

Below are shown the cross sections of the active plasma regions of both conventional (classic) type tokamak (CT) and so called “spherical” tokamak (ST) devices. Until 2010 many projects of the fusion-fission devices were based on the plasma device, which achieved the highest plasma parameters – e.g. conventional (classic) tokamak. In the last 15 years a rapid development shows another tokamak geometry, the so called “spherical” tokamak.

Fig. 4. Comparison of the plasma area of conventional and spherical tokamaks

Fig. 5. Comparison of projected development of conventional and spherical tokamaks [12]

Due to the limited space of the text it is not possible to discuss the merits and the drawbacks of both systems. Since this paper has to present the view point of different groups of investigators it is expedient to show the predictions for ST usage in power units.

Below is shown a system which, in my opinion, has a good chance to be implemented [13]. This is the project of the Russian Federation for the DEMO Fusion Neutron Source (FNS). The project is based on the tokamak design, something between the conventional and the spherical tokamak. The characteristics of the device are: radii of torus, respectively $R = 2.75$ m, $a = 1$ m, aspect ratio $A = 2.75$, superconducting coils (classical superconductors) for

the magnetic fields, $P_{\text{fus}}, \sim 40$ MW. In the blanket are mounted thorium modules for fission and fuel production. An important intermediate step of the project will be construction and commissioning in the near future of the medium size tokamak, T15MD (big radius of the torus $R \sim 1.5$ m) [14].

According to the opinion of Academician E. Velikhov, the Russian Federation will have DEMO FNS by 2035. Among other import project should be pointed out the magnetic mirror machines. They have many advantages in comparison with the Tokamak systems, most important is that they are much cheaper than the tokamaks [15]. The other magnetic confinement devices will not be covered here given the insufficient space.

Fig. 6a. Sectional view of the tokamak of Russian Fed., Kuteev et al 2015 VANT 38, N2, Fus. Ser. [11]

Fig. 6b. Composition of the device DEMO-FNS

Plasma Focus (PF) machines should be mentioned here for several reasons: (i) they are compact devices with high neutron yield, (ii) due to the non thermal mechanism of the fusion reactions in PF the proton – boron reaction can be accomplished there. In my opinion this reaction will have considerable application in 22nd century given that the reaction products there is no neutron yield in it – only fast alpha particles. Besides – the PF could work on the cascade principle of multiplication of

the neutron flow, which is used in another strand of nuclear energy investigations – the so called “electrical breeding” mentioned above. The plasma focus (PF) is a kind of Z-pinch discharge. Since the PF was known as a source of abundant neutron flux there had been several attempts to use it in hybrid systems. Clausse et al [16] show the theoretical possibility to create compact hybrid system based on PF using amplification cascade for the neutron flux.

Fig. 7A. Plasma focus device

B. Cascade amplification of the neutron beam. The shaded layers consist up to 8 % U²³⁵

C. Average magnification coefficient M

Fig. 8 below shows the project based on National Ignition Facility (NIF) concept for inertial confinement fusion [17, 18].

Fig. 8. Inertial confinement fusion project (laser fusion) of NIF.

Fig. 9. A graph of the thermal energy (left), that can be obtained during a 50 years life cycle of this LIFE hybrid reactor. On the right is shown the time diagram of the utilization of different isotopes in this project [18].

REMOVING THE DRAWBACKS OF COMMERCIAL NUCLEAR POWER

The experimental curves shown below [19] are amazing for many scientists, but they have sound reasoning, based on the Heisenberg infinity principle

given in the dynamic form by Shrodinger – Robertson. In this case coherent correlated states are formed. The mechanism explains the very high probability of some nuclear reactions, the absence of gamma radiation and radioactive daughter isotopes, as it is thoroughly shown by V. Visotskii and M. Visotskii in [20].

Fig. 10. Experimental results of decay of activity of radioactive Cs^{137} samples from light fission reactor water, in a vessel with syntrophic assembly of microorganisms. A drastic reduction of the time for decreasing of the activity of radioactive isotope is observed in comparison with the lifetime of the same isotope.

The explanation of the fast decrease of the Cs^{137} activity in the sample is the reaction going on for example in the last curve (green box) [19, 20]:

Acquiring a proton from the surrounding media the radioactive Cs^{137} isotope atom is transformed into a stable Ba^{136} atom, required for the rise of the colony. The reaction energy is positive and is equal to $\Delta E = 5.58 \text{ MeV}$. The physical principle of this action is to create short-term gigantic fluctuations in the energy of the proton under the influence of microorganisms and a tunnel transition that performs the synthesis reaction at room temperature. For the needs of a growing (evolving) biological system, certain ions may be required. Such may be potassium ions or barium, which is the "biological analogue" of potassium. Indeed, the ion radii of the two ions, Ba^{2+} and K^+ , are

very close: $R_{\text{Ba}} \approx 1.4 \text{ \AA}$ and $R_{\text{K}} \approx 1.33 \text{ \AA}$. Potassium is a vital trace element for the system and if it is efficient for the colony, the probability of its replacement with barium ion is significant, much greater than the probability of directly replacing potassium with cesium, whose ion radii are $R_{\text{Cs}} \approx 1.67 \div 1.69 \text{ \AA}$. More details for the processes gives the next figure since for the purpose are suitable isotopes with smaller life times. According to A. Kornilova the behavior of the Ba^{140} and La^{140} decay curves, (Figure 11) can be explained as comprising two stages: an initial period of 10 days when the microorganism association is adapted with the irradiation from the isotopes and subsequent one with a faster decay. In the first period a replacement of about 10 generations of microbial cultures occurs.

Fig. 11. Experimental results of decay of activity of Ba, La and Co radioactive samples from fission reactor water, in a vessel with syntrophic assembly of microorganisms [19].

As can be seen the decay of Co^{60} is not influenced by the microorganisms. In other words, the conditions set in the work [20] for implementation of low energy nuclear reaction (LENR) are not fulfilled in the case of cobalt Co^{60} .

Then the decreasing of the ^{140}Ba becomes two times faster than if should by specific decay time $\tau_{\text{Ba}} = 12.7 \text{ days}$ of the isotope. Since the decay time of La^{140} is $\tau_{\text{La}} = 40.3 \text{ hours}$ and this isotope is derived from Ba^{140} , the decrease of both activities will be determined by the Ba^{140} component in the sample. It is possible that the following transmutation reaction is taking place:

ΔE in this case is positive and it is 8.5 MeV. The MCT granules contain carbon. Samarium Sm^{2+} and calcium Ca^{2+} ions are biologic analogues and have close ion radius: $R_{\text{Sm}} \approx 1.12 \text{ \AA}$; $R_{\text{Ca}} \approx 1.06 \text{ \AA}$ in the two valence state. Therefore, the growing microbial association will support the reaction (6).

CONCLUSIONS

The advantages of the fusion-fission concept compared to "pure" fusion reactor are:

1. The thermal load and other radiations on the first wall and other structures of the fusion module are reduced by a factor of 5 to 50. Thus the goal of using energy from fusion plants will be achieved faster and more cheaply.

2. The problem of tritium reproduction will be solved easily. The 14 MeV neutrons cause fission acts in the blanket where the total number of neutrons strongly increases. From this total number, 1.8 of the neutrons can be used in the Li^6 layer for reproduction of tritium required for the fusion part.

Compared to the conventional fission reactor:

1. By application of the U^{238} and Th^{232} isotopes the nuclear energy storage on Earth will rise by more than 2 orders of magnitude.

2. The actinide (uranium) cycle closes in the reactor system. Therefore substantial reduction of nuclear waste at the expense of spent nuclear fuel and other reactor produced actinides is expected.

3. The hybrid system has high level of nuclear safety. The blanket, working in a subcritical mode, stops when the primary neutron flux from the fusion core stops.

4. The fusion-fission breeder reactors would be much more efficient than the existing fast breeder reactors.

5. The introduction of Th^{232} fuel will decrease substantially the danger of wide non regulated proliferation of nuclear materials associated with weapons.

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