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CURRENT PROBLEMS AND PROSPECTS OF NUCLEAR POWER

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The problem of energy production on a large scale for rapidly increasing world population is at the present of vital importance. As a consequence various ways of energy gain are now subjected to thorough and comprehensive analysis from the viewpoint of more and more rigorous and stringent criteria, the main are safe operation, commercial competition, reserves of energy sources and not devastating the earth. So, it becomes apparent that just in not distant future the energy production on a global scale should not consume oxygen and, consequently, not create carbon dioxide which accumulation in ocean waters could lead to catastrophic changes in the ecosystem of our planet the regenerative capabilities of which are constantly diminishing as a result of mankind activity. The unique way that can completely satisfies the above-mentioned conditions can be only nuclear power (NP). But the future NP should be safe, much more efficient and no producing radioactive waste. We give an outline of conceptual basis of such a nuclear power of future generation, which satisfy the criterion of energy sustainable development.

Keywords: *Nuclear power, safety, efficiency, radioactive waste, transmutation, ADS.*

INTRODUCTION

The increasing population of the world needs more and more energy to satisfy various and constantly rising requirements. Moreover, the prolongation of human life itself strongly depends, in the average, on the energy consumption per head as follows from Figure 1. Besides, the demand for energy grows faster than the increasing of population because one half is destined to the higher living standards.

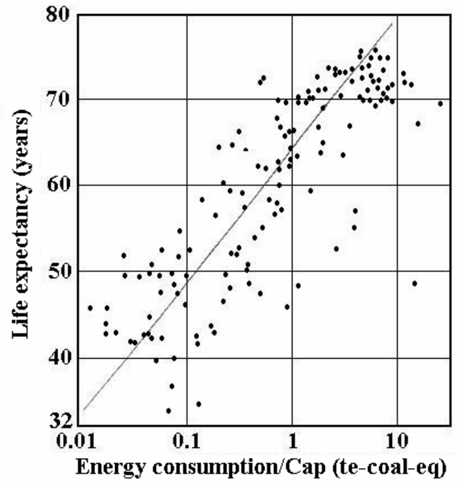

Figure 1. Average life expectancy 1980-1985 vs. energy consumption per head in 150 countries [1].

The main energy sources currently used on a global scale are: fossil fuels (gas, oil, coal), fast enough flowing rivers producing the so-called hydroelectricity and the binding energy of heavy nuclei which is the base of nuclear power. However, the total potential of hydroelectric power is estimated as not exceeding of about 10% of total world's energy requirement whereas the current share of nuclear power approximated ~15-17%. Contribution of other sources called as renewable (wind, tides, biomass, solar, wave and thermal water and geothermal) amounts to several percents of the total demands. Moreover, although very preferable and continually improving they are as a rule much more expensive and should be spread over large surfaces to collect a profitable quantity of energy. So, until now the relevant devices (like windmills, wave generators or solar batteries) are of local application being used mainly in isolated places. The same holds true for the profit from the magnitude of energy which now is simply squandered and can be saved, unless some new physics phenomena will be involved on the global scale, such as reliable room temperature superconductors or quite new fascinating and crazy approach to the use of electricity as, for example, by means of low-voltage devices supplied by local, even home, electrochemical sources [2]. In the last case the economy would be indeed significant - no dense high-voltage network, covering practically all surface of the earth, expensive to maintenance, material consuming, causing appreciable losses of electricity, spoiling landscapes and vulnerable to atmospheric, solar and sabotage activities.

The fundamental significance for the world energy policy has the problem of reserves of energy sources. At present it is found reliably enough that fossil fuels (gas and oil) suffice for about 50 years and 200 to 400 years (coal and lignite). Nuclear fuel sources are much wealthier, both fissile (uranium and thorium) and fusion (deuterium).

Within the approach of energy sustainable development, different ways of energy gain on a large scale are now subjected to thorough and comprehensive analysis from the viewpoint of more and more rigorous and stringent criteria, the main among them are ecological safety, commercial competition and reserves of energy sources (see, for example, [1,3]). Although presently, as far as it can be foreseen, a global energy crisis is, in principle, not to be expected and traditional kinds of energy production seem to be sufficient, nevertheless it is anticipated that between 2008 and 2010 a serious energy gap will arise which hardly could be filled by the renewable energy sources [3]. At the same time the specialists are more and more aware that just in not so distant future the energy production on a large scale should be no oxygen consuming and, consequently, no creating carbon dioxide which accumulation in ocean waters could lead to catastrophic changes in the ecosystem of our planet, as follows from recent investigations. Moreover, the regenerative capabilities of this ecosystem are continuously diminishing as a result of mankind activity. The unique way that thoroughly satisfies the above-mentioned criteria can be only nuclear power.

Nuclear power (NP) unlike other domain of human activity had been entangled from its very beginning in various negative prejudices following both from simply ignorance and erroneously understood competition, as well as from different political manipulations. Indeed, originally being a by-product and direct consequence of military application of nuclear physics and nuclear technology, NP gained among some part of population ill repute of inhuman technology, and even a peculiar monster unintentionally released and completely uncontrollable. This opinion has been aggravated by two fatal accidents in nuclear plants: at Three Mile Island and Chernobyl (see, for example, [1]). Later on, in more serious analysis the opponents tried to proof that NP have the use of artificially created privileges without which its existence would be unjustified from any reasonable viewpoint. Nevertheless, the comparative economical analysis clearly shows that although the present NP is far to use all its potential possibilities, it is quite competitive despite the fact that the imposed requirements of NP are much more rigorous than of other kinds of energy production [4]. Moreover, NP is a unique source of energy for spacecrafts and big submarines. It is also assumed to have a wide application in hydrogen production [5]. But the future NP must be safe, much more efficient and no producing radioactive waste. In the present work we give an outline of conceptual basis of such a nuclear power.

THE PRESENT STATUS OF NUCLEAR POWER

In 2001 there were in operation 439 reactor blocks throughout the world, which produced 16% of electric power [6]. It means that this percentage has been reduced by 4% as compared to the year 1999 although the number of reactor blocks in service increased by 3 [7]. Nevertheless, in the last decade (1988-1998) NP left behind all its main competitors (gas, rock-oil, coal and hydro energy) in respect of the pace of development and in Europe it held the second place as shown in Figure 2.

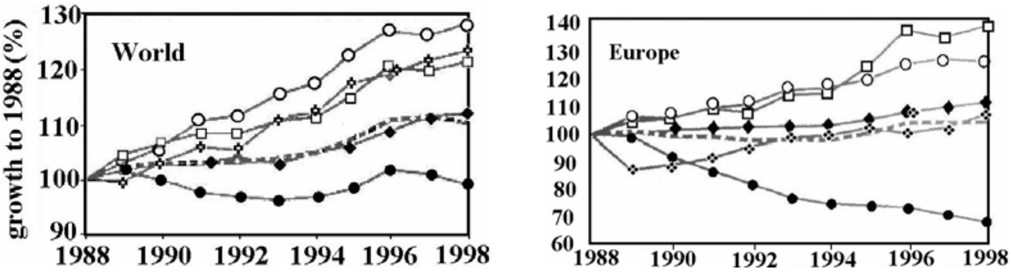

Figure 2. Increase of the use of primary energy with respect to the year 1988: left – World, right – Europe. Designations: ◆ - rock-oil, □ – gas, ○ – nuclear power, ● – coal, ♣ - hydro energy, ▬ ▬ - total use [8].

Current development of NP is considered as stable and permanent. Its present state is determined by two main factors: a global economic recession involving the apparent surplus of electric energy production (EP) and the transformation of EP market (see, for example, [6]). But in spite of present difficulties nuclear reactors, in contrast to the power stations burning up rock oil, gas and coal, are regarded to be, in particular, the most suitable heat source for hydrogen (H_2) production on a large scale [5].

Nowadays three scenarios of NP development are examined [9]: pessimistic, basic and optimistic. The total electric capacity of nuclear power stations (NPS) for the period from 2000 to 2020 is shown in Table 1.

It should also be stressed that the above estimations concern the currently functioning NP based mainly on light water thermal reactors.

Table 1. Total electric capacity of NPS for three scenarios of development of the world NP (in %) with respect to the year 2000 [8].

Years	2000*	2005	2010	2015	2020
Scenario:					
Pessimistic	100	101.2	100.8	98.2	88.0
Basic	100	103.4	108.0	113.5	115.5
Optimistic	100	106.5	118.1	127.8	138.9

*Total world electric capacity of NPS in 2000 was 350,6 GW.

CURRENT PROBLEMS

Present NP is quite competitive as compared to other kinds of energy production on a large scale and sufficiently safe as well. It is worthy mentioning that, for example, in USA the electricity charges of “nuclear” 1 kWh decreased in 80th to the degree lower than for the cheapest thermal electric power stations [6]. Nevertheless, in parallel with enormous and till now practically not exhausted potentialities NP has serious shortcomings, in particular, the release of hazardous long-lived and highly toxic radioactive wastes (RW) which, in addition to the ecological aspect could be used improperly. Moreover, in light water reactors that constitute the essential part of present-day NP no more than about 1% of excavated natural uranium is burned up only. The problem of passivation of RW remains so far open because their transmutation by means of reasonably available beams of particles (neutrons, relativistic protons and ions) is exclusively inefficient and so very expensive, at least as conducted by the traditional way (see, for example, [10]). Indeed, the experiments performed up to day in different laboratories show that this problem represents on the practical level a considerable challenge. The point is that even a precisely isotopically selected sample of a given radioactive nuclide is irradiated in the neutron flux of $\sim 10^{14} \mathrm{cm}^{-2}\, \mathrm{s}^{-1}$ intensity as the most efficient and usual, progressively other nuclides appear and during the first several years of irradiation the total radioactivity of the sample increases. For example, in the case of plutonium incineration the maximum of the sample radioactivity sets in at 8.2 years after the irradiation is started [11]. More complicated is the situation relative to other candidates for incineration: Am and Cu [11]. Moreover, owing to the intricate structure of neutron-heavy nuclei cross-sections, the efficiency of transmutation/incineration strongly depends on energy spectra of neutrons and this dependence, in turn, changes according to the conditions of irradiation. At the same time known are the results about the dependence of the direction of transmutation on the intensity of neutron fluxes [11,12] as illustrated in Figure 3.

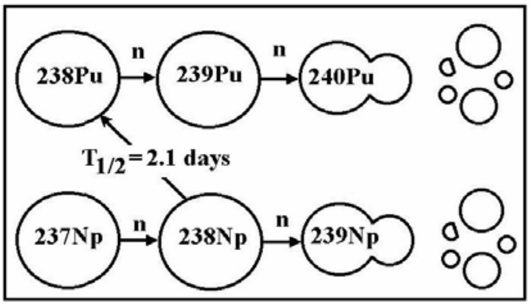

Figure 3. Neutron flux intensity dependence of higher actinides transmutation [12].

Much more complex situation occurs if the irradiated sample is not initially strictly determined isotopically but, for example, is simply taken as a piece of the spent reactor fuel. So, if we take into account that other radioactive and radiotoxic as well nuclides have, in general, very complex structure of their transmutation (see, for example, Figure 4) it becomes evident that the transmutation/incineration of radionuclides in bulk is an exclusively serious and challenging problem which requires versatile and comprehensive analysis to bring it in the future to the practical level on the large scale.

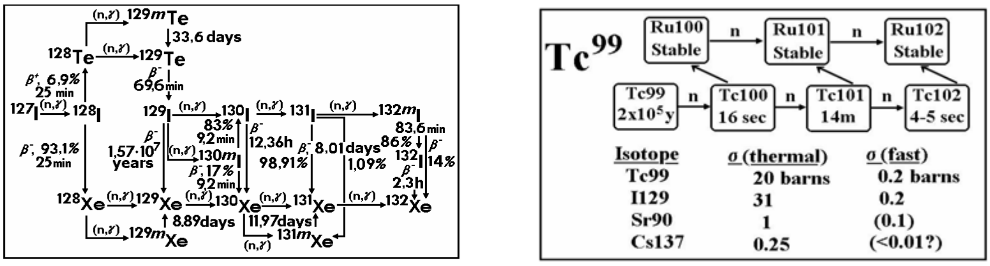

Figure 4. Chains of transmutation of iodine ^{127}I and ^{129}I (left, [13]) and ^{99}Tc (right, [14]).

During several last years intense investigations of the RW transmutation (RWT) process are conducted in many laboratories and first quantitative estimations have been obtained of the yield of some concrete processes for the major long-lived nuclides: ^{99}Tc, ^{129}I, ^{237}Np and ^{239}Pu occurring in acceptable conditions via the following reactions [15,16]:

$^{99}\mathrm{Tc}(t_{1/2}=2.11\mathrm{x}10^{5}\ \mathrm{yr.})+\mathrm{n} \rightarrow {}^{100}\mathrm{I}(t_{1/2}=15.8\ \mathrm{s})\rightarrow {}^{100}\mathrm{Ru}(\mathrm{stable})$,
$^{129}\mathrm{I}(t_{1/2}=1.57\mathrm{x}10^{7}\ \mathrm{yr.})+\mathrm{n} \rightarrow {}^{130}\mathrm{Tc}(t_{1/2}=12.4\ \mathrm{h})\rightarrow {}^{130}\mathrm{Xe}(\mathrm{stable})$,
$^{237}\mathrm{Np}(t_{1/2}=2.14\mathrm{x}10^{6}\ \mathrm{yr.})+\mathrm{n} \rightarrow {}^{238}\mathrm{Np}(t_{1/2}=2.12\ \mathrm{d})\rightarrow {}^{238}\mathrm{Pu}(t_{1/2}=88\ \mathrm{yr.})$,
$^{239}\mathrm{Pu}(t_{1/2}=2.41\mathrm{x}10^{4}\ \mathrm{yr.})+\mathrm{n} \rightarrow$ *fragments* (^{91}Sr, ^{92}Sr, ^{97}Zr, ^{99}Mo, ^{103}Ru, ^{105}Ru, ^{132}Te, ^{133}I, ^{135}I and ^{143}Ce) *having the half-life time of several hours up to several days.*

The following macroscopic transmutation rates of long-lived fission fragments have been deduced under conditions that a Pb target setup was exposed to 1GeV and 10 mA proton beam (using 1g samples) [15]:

6.7 mg of ^{239}Pu is transmuted per day,
3.3 mg of ^{238}U is transmuted in one month,
21 mg of ^{237}Np is transmuted in one month,
3 mg of ^{129}I is transmuted in one month.

So, a proposal has been put forward suggesting to use for transmutation a liquid target of RW circulating in the field of high enough energy and intensity relativistic particles beams when from the exposed target are gradually extracted stable nuclides [10]. The aim of the proposed program is a detailed study of the optimal conditions of such a dynamical process in dependence on energy and the kind of irradiating particles (protons, ions, electrons, gamma quanta), as well as the exposition time, circulation/extraction velocity and the degree of separation. It should be stressed that the problem of management and disposal of RW is the subject of international research programs on the large scale [17].

Other important problems facing the present-day NP are the low efficiency of uranium fuel used for energy production in thermal reactors, not exceeding about 1%, and the problem broadly called as nuclear safety.

PROSPECTS FOR NUCLEAR POWER

The existing knowledge in the field of nuclear physics enables to solve the above-mentioned problems in the complex way. Now one can single out the following steps of evolution of NP. The first one consists in the technological enhance the currently working thermal nuclear plants from the viewpoint of their efficiency, longevity and safety. In the second period it is forecasted a gradual replacement of thermal reactors by the fast ones which are much more efficient and generates practically inconspicuous amount of hazardous radioactive wastes although several important questions concerning their commercial operation are not yet solved such as, in particular, the problem of cooling material and fuel structure. During the third period quite new ideas of nuclear energy generation will be put into operation. So, according to rather common opinion based on concrete quantitative estimations the most prospective arrangements of future NP are subcritical nuclear reactors driven by accelerators producing high-currant beams of relativistic protons called as the Accelerator Driven Systems (ADS) [18-21]. Such arrangements are quite safe because the reactor or a system of reactors operates in deeply sub critical regime, i.e. at the effective factor of neutron multiplication ~0.94-0.98, whereas the missing part of neutrons is provided by spallation reactions initiated in heavy and massive target by a beam of relativistic protons from accelerator. Therefore, in order to switch off immediately all this arrangement it is enough to stop the proton fuelling. At the same time the ADS give the possibility to produce high intense flu (~10^{16}n/cm^{2}s) of neutrons with energy above ~1 MeV which are necessary for RWT. A schematic illustration of such an ADS (with one reactor) for RWT is shown in Figure 5.

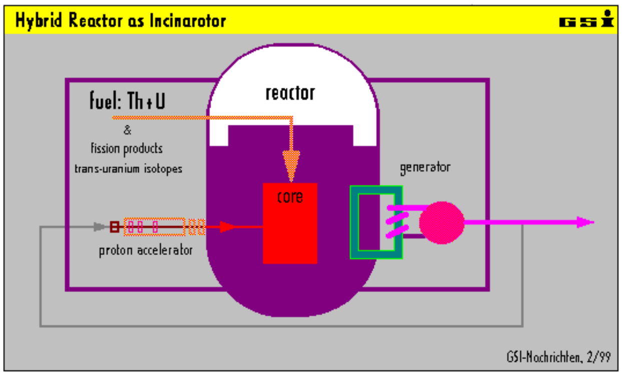

Figure 5. Schematic view of the ADS for incineration of RW [22].

In the simplest version, the ADS is based on one fast reactor which makes possible to burn up practically all natural uranium in the regime of closed fuel cycle when the nuclear splitting products which absorb neutrons are permanently removed from the spent fuel and the fuel is next enriching. Nevertheless, much more prospective seems to be now the ADS with cascade composition of two reactors as outlined in Figure 6. In this case the fast reactor operating in a hard neutron flux (~1MeV) is directly fuelling by spallation neutrons but the thermal reactor produces the main part of energy.

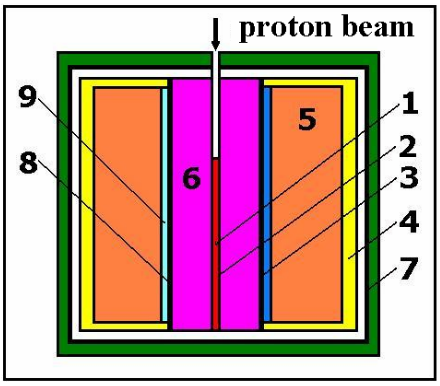

Figure 6. Schematic view of a cascade ADS: 1 – target, 2 – protective blanket, 3 – cadmium shield, 4 – reflector, 5 – active zone of thermal reactor, 6 – active zone of fast reactor, 7 – blanket of the system, 8 – isolation layer, 9 – layer of intermediate moderator [20].

CONCLUSION

Taking into account our present-day knowledge of NP and the experience gained during about fifty years of functioning of nuclear power stations, as well as the current and future needs in energy from the viewpoint of energy sustainable development, one can conclude that even the present state-of-the-art technology in this important branch of economy is quite competitive as compared to other ways of energy production on the large scale. Moreover, NP has an exclusively important advantage of no creating carbon dioxide and, therefore, no consuming oxygen. So, it does not disturb the equilibrium of the echo-system of our planet. What’s more, NP possess considerable potential possibilities, far to be exhausted till now, which will be set in motion as the necessary results of investigation in the field of applied nuclear physics, radiation material physics and radiation chemistry are accumulated. Nevertheless it is now almost certain that the future nuclear arrangements based on splitting nuclear reactions will be in the form of systems of fast reactors operating in deeply subcritical regime fuelling and driven by spallation neutrons produced in heavy extended targets by relativistic proton beams from accelerator (ADS). Such arrangements are able to burn up practically all natural uranium in the closed nuclear cycle and, in addition, to transmute and incinerate the radioactive waste from other sources used in medicine, industry, scientific research and military applications. Meantime works are in progress on the project of the high-temperature gaseous reactors (Pebble Bed Modular Reactor) with globular fuel elements, which are expected to be used, in particular, for the large-scale production of hydrogen (the so-called hydrogen economy) [4,23]. Small nuclear heat sources for the purposes of cosmic apparatus are also the subject of wide current discussion [24].

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المشكلات الحالية وآفاق الطاقة النووية

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يكتسب موضوع الإنتاج الوفير للطاقة - لسد حاجة المجتمع الإنساني المتنامي- أهمية حياتية، وبالتالي تخضع الطرق المتباينة لتوليد الطاقة للتحليل العميق والمكثف إنطلاقاً من معايير أكثر دقة وصرامة تخص التشغيل الآمن والتنافسية والحفاظ علي مصادر الطاقة دون تخريب أو إلحاق الأذى بالعالم أي لابد أن يضع الإنسان في اعتباره ألا يؤذي توليد الطاقة علي مستوي العالم في المستقبل غير البعيد إلي استهلاك الأوكسجين وتوليد ثاني أكسيد الكربون الذي قد يسبب تراكمه في مياه المحيطات في تغيرات كارثية تصيب محيط كوكبنا بتقلص مستمر في قدرته علي حفظ وتجديد إمكانيات البقاء للجنس البشري ونشاطاته. وتعتبر الطاقة النووية المصدر الوحيد لتوليد الطاقة الذي يحقق الشروط المشار إليها، مع التأكد من أن استخدام الطاقة النووية آمن وأعلي كفاءةً وغير منتج لمخلفات مشعة. ونعرض هنا إلي مخطط عام لأسس ومفاهيم مستقبل توليد الطاقة من النواة يتوافق مع معايير الأمان والحفاظ علي البيئة.