ACUTE PROBLEMS OF NUCLEAR ENERGETICS

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1. INTRODUCTION

Nuclear energetics possesses all necessary features to substitute gradually the considerable part of energetics based on fossil fuel. It should dominate in energetics of the future. Rise in energy production due to fossil fuel presents a number of problems observed presently over the world related with global deterioration in ecological balance. Besides that, the resources of fossil fuels are limited. During a half of the century nuclear energetics has evolved considerably. On a global scale, more than $1000 billion was invested in nuclear energetics. In 1999, in 33 countries 430 nuclear power units of the total power of 350 GW produced 2300 billion kilowatt-hours of electric energy.

Nevertheless, modern nuclear energetics is experiencing difficult times. It came under criticism, up to complete prohibition. Reasons for that are potential disasters with large ecological and economic losses, accumulation of highly radioactive long-lived nuclear waste, proliferation of nuclear weapon and danger of nuclear diversion associated with nuclear energetics. In this connection, the necessity for development of nuclear technologies arose which should be directed towards solving the following main tasks [1]:

1. Almost unlimited availability of fuel resources due to effective use of natural uranium, and, later on, thorium.
2. Exclusion of severe accidents with radioactive releases demanding evacuation of the population with any failure of equipment; wrong operations of the personnel, and external effects mainly due to features intrinsic to nuclear reactors and their constituents.
3. Safe energy production and waste utilization with minimum affecting the environment on account of closed fuel cycle with incineration of long-lived actinides in the reactor and transmutation of fission products and safe disposal of radioactive waste (RAW).
4. Maximum blockade of channels for proliferation of nuclear weapon associated with nuclear energetics and provision of reliable protection for nuclear fuel from unauthorized application.
5. Economic competitiveness and attractiveness due to low cost and provision of the necessary level of the fuel reproducibility, high efficiency of thermodynamic cycle, solving the problem of safety without complicated construction and imposing extreme demands on equipment and personnel.

On estimation competitiveness of nuclear energetics in comparison with energetics based on fossil fuel total losses, which accompany energy production and distribution should be taken into account. In that case, besides the technological cost of electric power, an "external" cost should be accounted that lies, in terms of money, in adverse influence on health of population associated with chemical and physical pollution of the biosphere.

Presently, in nuclear energetics large sums are spent on provision of internal safety of energy production and the safe handling with radioactive waste. At the same time, pollution of the biosphere by fossil energetics is not accounted in calculation of the energy cost. This damage involves both environmental contamination with ashes and smoke and enormous quantity of CO_2 released into the atmosphere that lead to global greenhouse effect, and, as a consequence, to extreme alteration of climate that is observed presently. Account of these facts through quotation and fines would lead to considerable raise in cost energy produced on the base of fossil fuel.

In general, presently following lines of the development of energetics of the future became noticeable:

1. Energetics based on reactors on thermal neutrons. This is a highly developed branch with advanced technologies for energy production and developed systems for provision of both internal and external safety. There are prospects for this reactor group that would enable their functioning during several decades. At the same time, difficulties are visible of full-scale application of this reactor group associated with insufficiency of fuel resources in ^{235}U and generation of tremendous amount of nuclear waste.
2. Reactors on fast neutrons (FNR). Their development is associated with their capability to extended reproducibility of nuclear fuel, therefore they are predicted to be extensively used in the future. Presently, several reactors on fast neutrons with sodium coolant operate over the world. Even more safe and complicated coolants of heavy metals are developed. Lessening of demands on quickened fuel reproducibility in the form of ^{239}Pu allows to increase efficiency of FNR operation and eliminate a possibility of application of nuclear weapon for sabotage. According to estimation of Russian researchers [1,2] by 20th and 30th full-scale application of reactors of this group will have taken place for production of nuclear energy. At the end of the century the operation of FNR will be converted from the application of U-Pu fuel to ^{232}Th-^{233}U fuel cycle.
3. Thermonuclear fusion proposes a long-term safe energy source with almost inexhaustible fuel resources and significant ecological advantages. According to estimations of the specialists [1] it is assumed that thermonuclear energetics may achieve the level of practical application in the middle of 21st century and become of greater importance by the beginning of 22nd century.

Combination of fusion and fission nuclear energetics is possible in which fusion reactor, due to the powerful neutron flux, will enable a high rate of expansion of the FNR-group and will be used as an intense neutron source in energy installations.

4. The accelerator driven power installations (ADPI). This kind of energetics is a complex combining a powerful proton accelerator and a subcritical nuclear reactor. The conception of ADPI has been being worked out for considerable time. First, it was assumed to use proton beams as a support for production of fission materials, and then various proposition arose to apply the ADPI as an efficient energy source and for elimination of generated nuclear waste through incineration of transuranic elements and transmutation of long-lived radioactive waste.

There exist various approach to conceptual schemes of ADPI and their position in energetics of the future. Development in this direction is being carried out in USA, Russia, Pan-European Science and Research center CERN, Japan, France, Korea, and others. Presently, these designs differ in conceptual peculiarities and evaluation of their position in energetics of the future.

In the well-known documents defining the strategy of the development of nuclear energetics in Russia [1,2], in the nearest decades a very modest position is assigned to ADPI, though research teams from leading organization in the field of nuclear energetics and accelerating technologies [3] are engaged in development in this line of investigation. In these documents the task of development of subcritical reactors as powerful independent energy sources is not posed. Many propositions deal with subcriticality of thermal reactors. Such a “support” does not require changing radically design and technological approaches.

A completely different method of addressing the problem the research team from CERN headed by Carlo Rubbia uses. CERN reports [4,5,6,7] and reports at International conferences [10,11] contain the results of these works. In these works the statement is justified that the role of subcritical reactors called “Energy Amplifier” (EA) in energetics of the future is dominating, and the terms of putting into operation such presentation and commercial installations are rather short.

2. CONCEPTUAL AND TECHNICAL PECULIARITIES OF ENERGY AMPLIFIER

EA is a complex operating on fast neutrons in subcritical mode that originated at the interface of accelerating technologies and technologies of energy production with use of the fission reactions.

EA is based on the subcritical reactor with the multiplication coefficient for neutrons of 0.96-0.98. The deficiency of neutrons associated with subcriticality is compensated from an external source. Presently, the most efficient neutron sources are spallation-reactions of heavy nuclei (e.g., lead, tungsten, uranium) on their bombardment with protons with energy of ~1 GeV.

As a neutron moderator melted lead is used that conserves the hard neutron spectrum for a long time that enables high fission ability of highly active transuranic elements. The hard neutron spectrum gives a possibility to choose different combinations of fuel mixtures. The most preferable fuel for such reactor is a mixture of natural thorium with various fission materials. Thorium possesses a very low cross-section of the fission reaction, but ^{233}U produced from ^{232}Th in the chain of nuclear transformations $^{232}\text{Th} \rightarrow {}^{233}\text{Pa} \rightarrow {}^{233}\text{U}$ has the fission ability comparable with that of ^{235}U. As an original fuel material the mixture of thorium with weapon plutonium or thorium with transuranic elements isolated from nuclear waste (“dirty plutonium”) is used. Combination of thorium with ^{235}U is possible.

The process for production fuel elements from the thorium-transuranium mixture is much simpler than in the case of a fuel in traditional reactors on slow neutrons. Thorium is mono-isotopic, and transuraniums are loaded without separation by elements. At the same time, production of enriched uranium as a fuel for LWR requires multi-staged treatment: isotopic separation, preparation of the working mixture, fabrication of fuel elements. Besides that, to generate the same amount of energy far less amount of thorium is necessary. For example, for production of thermal energy of 3 GW·years it is necessary to have only 0.78 t of thorium instead of 200 t of natural uranium.

In Energy Amplifier lead is used as a moderator. It serves also as a target for neutron generation in the spallation-reaction and as a natural convection heat agent, the medium for location of fuel units and shielding the reactor vessel from radioactive radiation. The high density of lead and the large expansion coefficient allow to achieve good convection even for generation of high power. The large expansion coefficient creates the negative reactivity coefficient that eliminates spontaneous gain in reactivity in the case of its unforeseen heating. Finally, it is an excellent shielding material absorbing the most part of radiation generated in fuel elements.

Moderation of neutrons of 1 MeV to the thermal energy (0.025eV) in the isotropic diffuse medium of lead will occur through elastic scattering, with that neutron undergoes ~1800 collisions during 3 ms with the integral path length of 60 m. Thus, neutron energy in lead will decrease adiabatically with energy loss in one act of collision by less than 1%, that causes the extremely hard neutron spectrum in lead.

The reactor part of EA is shown in the Fig.1.

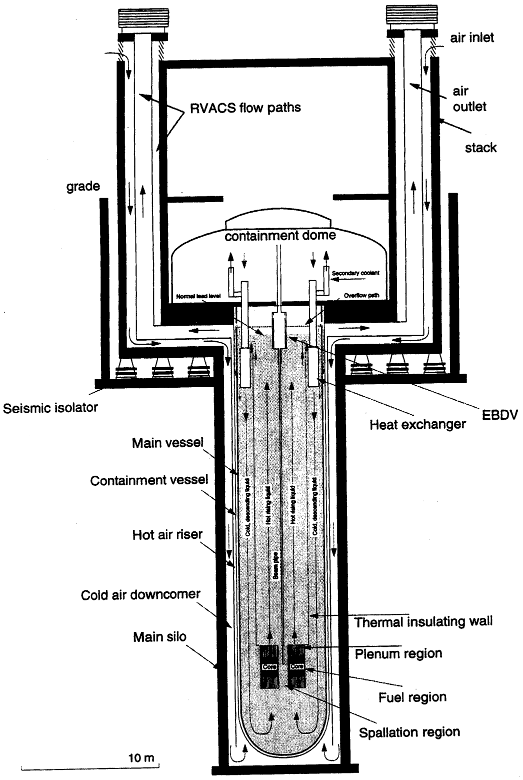

Fig 1. General layout of the Energy Amplifier reactor

The core is enclosed in a vessel of the diameter of about 6 m and 30 m in height filled with liquid lead (10 000 t). That vessel is a carrying construction for the main equipment that is introduced and assembled inside. The total mass of the vessel (without lead) is about 1500 t. The volume of the vessel is divided in three parts along the height: target-fuel-breeder; area of convection; area of heat exchange.

A proton beam with the current of 20-30 mA after acceleration is injected into the vessel through the transport system. In front of the vessel a 90° magnet is installed that decline the proton beam, and accompanying neutrons are removed to the graveyard. The diameter of the beam is about 15 cm. The construction of the beam channel allows to decline the beam during approximately 1ms that is insignificant in comparison with the inertial mode of operation of the nuclear system. The beam is focused with standard quadrupoles, passes through ion pipe and is released into the target of liquid lead through a tungsten window 3 mm thick. Tungsten was chosen because of its properties: high melting point (3410°), high mechanical rigidity, low activation and low corrosion in liquid lead. The basis for EA is extremely diffuse medium (liquid lead) in which fuel elements are incorporated. The core is divided in three concentric areas:

First area (a spallation-target) does not contain fuel; it is filled with liquid lead. In this area the beam of particles produces primary neutrons. Radial dimensions of this volume should be large enough to make neutron spectrum relatively mild in the process of multiple elastic scattering on nuclei of lead. Neutron spectrum on the first fuel element should be mild enough to provide minimum radiation damage of the shell and to make irradiation of the fuel elements uniform. In practice, the radial size of the spallation-zone is about 40 cm.

Second zone is the area of main fuel (in the general case this zone is subdivided in two parts: internal and external ones).

Third zone, the zone of breeding, with decreased concentration of fission material. It is meant for compensation neutron losses in the process of burn up as fission fragments are produced.

The rated power of 1500 MW requires 27.3 t of the oxide fuel mixture with the average power density of 55 W/t. The average power of burn up is 100 GW/t during 5 years of operation. The equilibrium breeding concentration of ^{233}U in respect to ^{232}Th is 0.126. With such concentration there would not be any problem while operating with k=0.98.

The subcritical rector on fast neutrons F-EA possesses considerable advantages over thermal version of T-EA [4]:

1. Due to the fact, that the relative concentration of the fuel for breeding equilibrium state on fast neutrons is almost 9 times higher than for thermal ones, the rate of incineration is 4 times more and, respectively, the fuel mass for the same energy yield is 9 times less.
2. When operating on fast neutrons, the relative concentration of fission material in equilibrium state rises in time almost by 10%; this fact is used for compensation of neutron losses to capture intermediate ^{233}Pa. For thermal neutrons this correction is negligible.
3. The factor of fast nuclei fission gives an additional amount of neutrons, that allows to maintain the stable operation during a long time without recharge of the fuel.
4. The fast neutron flux in breeding equilibrium state is 20 times higher, that allows to incinerate efficiently long-lived radionuclides.
5. The capture cross-section of fast neutrons with ^{233}Pa is almost 40 times less than in the case of thermal neutrons, therefore even with high neutron fluxes this capture is 0.56 from the value corresponding to thermal neutrons.
6. Relative alteration in reactivity on account of the large life ^{233}Pa after switching on or off the installation would be almost 2.5 times less, despite the fact that rate of burn up for fast neutrons is 4 times higher.
7. Energy amplification for T-EA is, as it is stated in [4], G=20-30, that is obtained with effective multiplication factor k=0.92-0.95. Thus, energy production for T-EA is limited by the value of 30-50 GW d/t. The low value of k in this case is due to relatively large variations in power which are caused by generation of ^{233}Pa and ^{135}Xe that leads to the risk of criticality.
8. The wide band of fast neutron energies is favorable for receiving maximum probability for fission of actinides.
9. The cross-section of neutron capture with fission fragments for fast neutrons is less than for thermal neutrons. That implies a possibility to

increase considerably the operation time between overcharges.

3. ENERGY AMPLIFIER WITH THE FUEL BASED ON ^{238}U

Application of fast neutrons in the subcritical reactor of the Energy Amplifier type opens up great opportunities for application of various fuel combinations. In this connection, U-Pu fuel mixture is of large interest; here depleted uranium could be used which reserves are extremely large. The cycle of breeding based on ^{238}U is described by the chain of transformations

$$^{238}U + n \rightarrow \gamma + ^{239}U \rightarrow \beta^- + ^{239}Np \rightarrow \beta^- + ^{239}Pu.$$

In the mode of operation with thermal neutrons, application of plutonium as a fuel is not efficient because of its low reactivity. As one can see from the table 1, this cycle has certain advantages over the thorium version, which lie in higher reactivity and shorter half life of intermediate ^{239}Np (2.1 day); that decreases significantly the reactivity drop with power.

Table 1. Characteristics of the F-EA based on ^{232}Th and ^{238}U fuel cycles [4]

Parameters	^{232}Th	^{238}U
Neutron flux, $cm^{-2} \cdot s^{-1}$, ϕ	$2{,}33 \cdot 10^{15}$	$5.967 \cdot 10^{15}$
Burn up rate, W/g,	60	120
Breeding ratio, ξ	0.126	0.190
Variation limits, $\Delta\xi$	$+0.388 \cdot 10^{3}$	$- 6.00 \cdot 10^{-4}$
$N(^{233}Pa)/N(^{233}U)$	0.0208	
$N(^{239}Np)/N(^{239}Pu)$		$3.66 \cdot 10^{-3}$

The breeding ratio ξ for ^{238}U is somewhat higher than for thorium, though the amount of intermediate ^{239}Np is less, mainly due to the shorter life. However, the plutonium component for ^{238}U - ^{239}Pu mixture will be quickly transformed in a mixture of isotopes decreasing reactivity asymptotically. The advantage of the F-EA operating on this fuel over traditional fast breeder lies in the fact that the excess of neutrons in EA may be used for more prolonged burn up typically 200Gw·days/tonne with presence of fission fragments if initial burning cycle occurs with the concentration of fuel material below breeding equilibrium.

4. ENERGY AMPLIFIER IN THE MODE OF PLUTONIUM INCINERATION

Plutonium and higher actinides (Am, Cm, Cf etc) accumulated as a result of operation of civil nuclear reactors, and plutonium set free from military nuclear arsenals give serious concern. In the Table 2, the amount of radioactive waste is given with the world production of electric power of 400 GW by 2010 [8]. To that it is necessary to add 300 t of weapon plutonium, 180 t of which are in warheads, and 100 t should be reprocessed. Plutonium is found in various materials, the major part - in the nuclear reactor waste.

Table 2. The amount of radioactive waste that will have been generated by 2010 with world electric power production of 400 GW.

Total amount of nuclear waste	300000 t
Plutonium isotopes	3000 t
Neptunium isotopes	140 t
Americium and higher actinides	120 t
Long-lived fission fragments	
^{99}Tc	250 t
^{135}Cs	90 t
^{129}I	60 t

Significant advantage of the thorium-transuranium fuel cycle is incineration of most highly active and long-lived components of nuclear waste. Besides that, it is possible to use a part of neutrons for transmutation of most active long-lived nuclides, fission products which require large volumes of disposal. At the same time, taking into consideration large distant of ^{233}U in respect to transuraniums, generation of higher actinides will be reduced to an insignificant amount. Thus, there is no need in construction and maintenance of costly geological disposals.

In EA, the original fuel in the course of a number of cycles is incinerated completely. With that new actinides are generated that then will be introduced again into the fuel for following cycles. After each download for fabrication new fuel mixture a certain amount of make-up fuel is added to compensate the burnt-up fuel transformed into fission products which are removed. Original nuclei of the fuel experience a number of transformations caused by neutron capture and spontaneous decay until they are not split completely. First of these transformations is a reaction of initial breeding that runs continually and is a source of fissile ^{233}U even with large time of burn up. In the course of that secondary processes occur of generation of new materials from thorium to californium which contribute to the process of burn up. After the nominal term of burn up 150 GW d/t actinides are separated and fresh thorium is added.

Amount of Np and Pu in asymptotic concentration after 20 cycles is 0.2% and 0.1%, respectively, with energy production of 3000 GW d/t. Higher and more dangerous actinides, such as americium and curium never achieve significant concentration. At the same time, plutonium concentration when recharged from LWR is 1.1% with production of 33 GW d/t. Amount of all transuraniums generated in EA per a unit of energy is almost 3 orders lower than in a conventional LWR.

Thus, contrary to a conventional reactor, generation of actinide waste is almost absent, as they are introduced to a new cycle on every recharge until they reach asymptotic concentration, therefore radiotoxicity induced by them is not high.

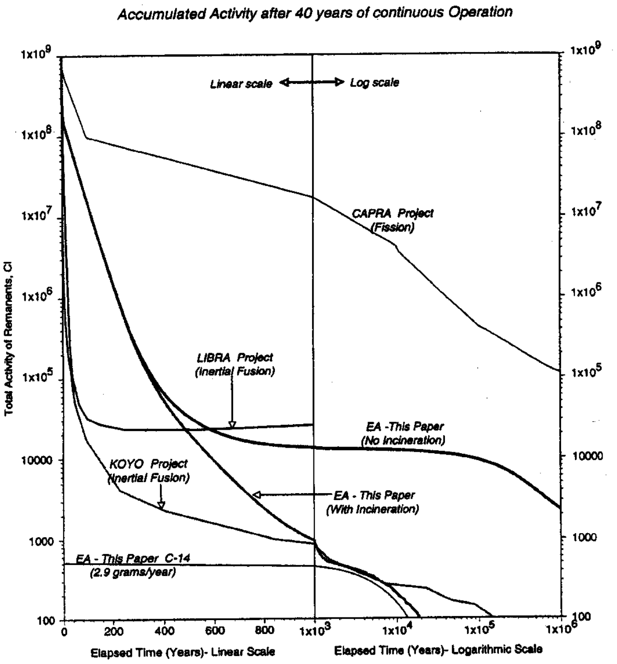

Fig.2. Accumulated activity of Remnents as a function of the time elapsed after shutdown for a different of fission and fusion conceptual projects aiming at minimizing the radio-active waste.

The accelerator driven energy installation operating in the mode of incineration of radioactive waste allows to achieve the lowest level of radiotoxicity. There is a number of other projects of "pure" nuclear energetics. In the paper [4] comparison of different concepts of energetic installations is given from the viewpoint of generation of radioactive contamination. In the Fig.2 radiotoxicity in Ci versus time for installations of different types is given after 40 years of operation per 1 GW of electric power. Installations of fast breeding based on plutonium incineration marked in the Fig.2 as CAPRA form extremely high level of radioactivity. The fusion reaction promises purest energy. Different projects of fusion differ considerably in generation of radioactive materials. The projects of inertial fusion LIBRA and KOYO are much pure. The radioactive level of materials in the case of magnetic fusion is 3 orders higher. The concept of Energy Amplifier with and without incineration of long-lived fission fragments is among the best concepts of fusion.

From the Fig.2 it is seen that on being kept in intermediate disposal for 1000 years, activity stabilizes at the level of $1.7\cdot10^7$ Ci for fast breeder, $2.35\cdot10^4$ and 400 Ci for fusion installations, $1.39\cdot10^4$ and 950 Ci for F-EA with and without incineration of long-lived radionuclides, respectively.

Besides high purity, accelerator driven energy installation of this type possesses a number of other advantages similar to the concept of fusion, such as noncriticality, environmental safety, and abundant fuel resources. However, there are no technologic barriers, while for fusion main problems remain unsolved.

REFERENCES

1. The International project "Energetic provision for the stable development of the mankind, cardinal solution of nonproliferation of nuclear weapon ecologic sanitation of the planet of the Earth". Russian Science Center "Kurchatov Institute" INE-6213/3. Moscow – 2001. 118 pages (in Russian).
2. The strategy for the development of nuclear energetics in Russia in the first half of the XXI century. Main concepts. Ministry for Nuclear energetics of the Russian Federation. Moscow 2000. 32 pages (in Russian).
3. A.S.Gerasimov, G.V.Kiselev. Research and design problems in creation of accelerator driven nuclear installations for the transmutation of long-live waste with simultaneous energy generation (Russian experience) "Physics of elementary particles and atomic nucleus", 2001, vol.32, # 1, pp.143-188 (in Russian).
4. C.Rubbia, J.A.Rubio, S.Buono et al. Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier. CERN/AT/95-44 (ET).
5. C.Rubbia, S. Buono, E.Gonsales et al. A Realistic Plutonium Elimination Scheme with Fast Energy Amplifier and Thorium-Plutonium Fuel. CERN/AT/95-53 (ET).
6. C Rubbia and J.A.Rubio. A Tentative Programme Towards a Full Scale Energy Amplifier. CERN/LHC/96-11 (EET).
7. J.P.Revol. Particle Physics Contribution to the Elimination of Nuclear Waste.CERN-SL/99-067 EET.
8. C.Rubbia,S. Buono, Y Cadi and J.A.Rubio. Fast Neutron Incineration in the Energy Amplifier as Alternative to Geologic Storage: the Case of Spain. CERN/LHC/97-01 (EET).
9. The TARC Collaboration. Neutron-Driven Nuclear Transmutation by ARC in Accelerator Resonance Crossing . CERN-SL-99-036 (ETT)
10. C.Rubbia et al. "A High Gain Energy Amplifier Operated with Fast Neutrons", AIP Conference Proceedings, Las Vegas, July 1994, 346.
11. C.Rubbia. Status of the Energy Amplifier Concept. Proceeding of the II Intern. Conf. ADTD and Application, Kalmar, Sweden, 1996, p. 35.