CURRENT STATUS OF THE SCIENTIFIC ACTIVITY IN RUSSIA ON HLW TRANSMUTATION AND USE OF WEAPON-GRADE AND POWER PLUTONIUM IN SUBCRITICAL SYSTEMS DRIVEN BY PROTON ACCELERATOR

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Features of neutron fuel cycles with ENF as well as FP's and actinides transmutation in ENF are analyzed in the paper: fuel type, fertile materials, neutron consumption, second radioactivity, change in FP's and radiotoxicity of actinides. Use of the weapon-grade and power plutonium in the ENF is considered too. Information on different design version of the ENF blanket including study of the sectional blanket with neutron valves, its performance, problems of the ENF design, R&D program including neutron source driven by 56 MeV "Istra" proton linac is given. Proposals on joint scientific cooperation are discussed.

1. MAIN IDEAS

1. Decrease in the amount of the long-lived radioactive waste (LLRW) produced by the atomic power and defence industries with the help of a transmutation process.
2. The use of electro-nuclear facilities (ENFs) in combination with specialized fast reactors for LLRW nuclear transmutation.
3. The use of ENFs in the promising atomic power industry to close the nuclear fuel cycle (NFC) as to fissionable materials and fission products with concurrent power generation.
4. The application of new, more safe technologies in the ENFs implementation compared to NPPs reactors, particulary in the case when weapon-grade plutonium is used.
5. Possible support of the LLRW incineration (transmutation) by public and population.
6. A need for-joining forces of and co-operation between different countries to implement the LLRW transmutation processes.

2. SHORT INTRODUCTION

There are two important problems in modern atomic power industry: NPPs' safety and high levelradioactive waste (HLW). In most countries including Russia the main strategy of the HLW management is HLW storage in solidified form in surface burial with further geological disposal. The data about HLW amount in Russia could be cited as an example (see Table 1) [1].

It can be seen from this Table that the main contribution constitute HLW produced in spent nuclear fuel (SNF) reprocessing plant. At the same time HLW produced by NPPs are several orders of magnitude less than those from a SNF reprocessing plant. On the basis of data from Table 1 an unexpected conclusion could be made that nations possessing NPPs and not performing SNF reprocessing or delaying it could not seemingly to hurry up with development of alternative HLW management technologies. At the same time as reserves of the natural uranium become more depleted the SNF reprocessing will be necessary. Therefore all nuclear nations should be interested in developing alternative HLW management technologies even now since development of new technologies is time consuming. At the same time in those nations where SNF reprocessing is performed development of alternative technologies is necessary since the HLW amount will constantly rise with time. In this case the social aspect has to be taken into account implying that part of the population is against the construction of storage facilities on the territory where they live.

In the last few years attention of experts from various nations is attracted by a transformation (transmutation) of the long-lived HLW in stable nuclides in a neutron flux. A large number of papers and reports devoted to transmutation and presented at international conferences demonstrates that.

146 papers have been presented at ICENES-93 conference in Japan including 33 dealing with HLW transmutation (12 papers on transmutation in fast reactors, 20 papers on transmutation in electro-nuclear facilities). At GLOBAL-93 International Confe rence held in Seattle, USA on September 12-17, 1993 there were:

- 19 papers on transmutation in fast reactors;
- 13 papers on transmutation in thermal reactors;
- 26 papers on tramsmutation in electro-nuclear facilities;
- 2 papers on transmutation in fusion facilities;
- 12 papers on nuclear data for transmutation.

A large number of interesting papers on transmutation in proton accelerator driven subcritical systems have been presented at International Seminar organized by ITEP in Moscow in May 1994 and at International Conference in Las Vegas, USA in July 1994 organized by LANL.

For purposes of clarity of further presentation let us explain the term of "electro-nuclear facility" which is used in present paper. The ENF consists of a subcritical core (blanket) with external neutron source in the form of neutron generating target and proton accelerator. ITEP and its Director, Professor I.V. Chuvilo is a scientific supervisor in R&D on ENFs in Russia. ITEP combines forces of 7 Russian research institutes and design organizations: Moscow Radio Technical Institute, Institute for Inorganic Materials (Moscow), Radium Institute (S. Petersburgh), Institute of Experimental Physics (Arzamas-16), Institute of Technical Physics (Chelyabinsk-70), Power Physical Institute (Obninsk), Design Bureau for Machine Building (N. Novgorod), Design Institute for Power Technology (S. Petersburgh) with the total number of people taking part in this activity accounting for appr. 300.

Besides, work on different ENF versions is being conducted in Moscow Physical Engineering Institute, Research and Design Institute for Power Technology (Moscow), Atomic Power Institute (Obninsk), High Energy Physics Institute (Protvino, Moscow Region), and Joint Institute for Nuclear Research (Dubna).

ENF R&D program is supported by the Russian Ministry of Atomic Power.

International Science and Technology Center (ISTC) in Moscow has made a decision to fund over a period of 2 years conceptual investigations on HLW transmutation and weapon-grade plutonium conversion in ENF conducted by Russian institutes. Unfortunately, the means allocated for this account for 30% of necessary amount.

Because information concerning the status of work on ENFs in Russia is presented at International Information Exchange Meetings for the first time, the presentation of general concept approaches to ENFs development is given in this paper along with particular results and proposals.

3. ITEP APPROACHES TO ENF DEVELOPMENT

ENF represents a new type of nuclear power facilities which in ITEP opinion should be introduced in atomic power industry of the 21st century. While conducting conceptual investigations and developments on ENF the ITEP experts are guided by the following criteria:

1. It is expedient to use the positive experience available and technical approaches verified in the atomic power industry, properties of inherent self-protection in particular, passive safety systems, "in depth protection" principle, etc. The main criterium in this case is the rise in the ENF nuclear and technical safety compared with NPP.
2. Experimental investigations should be conducted to substantiate new technical approaches proposed, first of all ENF blanket as the most complex and important unit for the purpose of safety.
3. Experimental work should be done on nuclear data base primarily for radionuclides to be transmuted.
4. At the stage of conceptual investigations it is expedient to study various versions of targets and blankets with estimates of their possible implementation, determination of technical and economical characteristics and choice of one version for further development.
5. The ENF operation should be performed with positive power balance and decrease in radiotoxicity compared with initial level.

4. ENF POSSIBLE OPERATION MODES AND FUEL CYCLES

The availability of the external neutron source makes its possible to consider different modes of the ENF operation and fuel cycles correspondingly. The following ENF operation modes could be noted:

1. A transmutation mode without power utilization.
2. A transmutation mode with concurrent power generation and utilization.
3. A mode with power generation and utilization as well as new fissionable materials production and HLW transmutation.
4. A mode of power generation and new fissionable materials production.
5. An after-burn mode for power generation with use of the NPP spent fuel assemblies as nuclear fuel.

The ENF can also serve as high intensity neutron source to produce radionuclides with high specific activity and for research purposes.

The ENF can have various fuel cycles depending upon operation mode. The following materials could be used as fuel materials for transmutation modes: enriched uranium, power and weapon-grade plutonium, actinides (in mixture with plutonium and without it), and ^{233}U. The depleted uranium and thorium could be used as fertile materials for production of the new fuel.

The possibility to implement in the ENF the following fuel cycles (FCs) could be indicated:

1. The uranium FC. In this FC version various uranium fuel could be used in blanket: 90% enriched uranium released as the result of nuclear disarmament, regenerated uranium produced after multiple irradiation and reprocessing cycles of the SNF with high content of ^{232}U and ^{236}U.
   Actinides and fission products (FPs) could be loaded into the blanket in various combinations and proportions for transmutation purposes. The depleted uranium without any restriction in ^{235}U content should be loaded into the blanket in plutonium production mode. ^{233}U could be used as a nuclear fuel in the ENF blanket too.

2. The plutonium FC. The plutonium fuel with different isotope composition: weapon-grade plutonium only, or power plutonium only, or their mixture could be loaded into the blanket in this version. Actinides and FPs could be loaded into the ENF blanket for transmutation purposes. The depleted uranium could be used for the purpose of nuclear fuel reproduction in the ENF blanket. Neptunium or ^{238}U included into plutonium fuel could be used for special purposes of the weapon-grade plutonium de naturization.

3. The uranium-thorium and plutonium-thorium FCs.The enriched uranium or plutonium is used as a nuclear fuel in these FC versions (thorium is used as fertile material for ^{233}U product ion purposes).

4. The actinide FC. In this version alternative actinides in various combinations with FPs are used as a nuclear fuel of the ENF blanket for transmutation.

In what form the fuel, fertile, and target materials are expected to be used has been of interest. Two main alternatives of fissionable fuel materials application is possible: in a solid and a liquid form. Each alternative has its own advantages and disadvantages. If the available experience in production of the nuclear fuel for NPPs is kept in mind, it is advisable to chose dioxide fuel in zirconium cladding. It will be a MOX-fuel in the case of power or weapon-grade plutonium. In recent years Russian experts are conducting investigations on cermet and nitride fuel with increased burnup level. In the last few years some research groups in LANL, JAERI, ITEP are being conducted investigations on liquid fuel based on fluoride molten salts of Li-BeF_2-ThF_4-PuF_4 type.

However, in the case of 3-5% actinides addition into the MOX-fuel its radiation resistance should be experimentally verified which requires substantial expenses and is time consuming.

The advantage of liquid fuel is the absence of radiation resistance problem, the possibility to break with metallurgical production of fuel assemblies, reduction in amount of FPs and fissionable materials in the core, etc. The main objection in Russia against liquid fuel lies in the absence of technological basis for its implementation in atomic power industry, rather complex technical problems emerging in reactor facility, etc. It could be argued that the problem of liquid fuel application advances the needs of the atomic power industry at the present time. However, R&D should be conducted on prospects and possibilities of the liquid fuel application in ENFs to have a basis for decision making.

The variety of the above mentioned operation modes and fuel cycles in the ENF requires certain priorities to be determined to concentrate small resources available in one or two R&D lines. For this purpose, systematic investigations have to be pursued which are not performed yet because of the lack of funding. But priorities in the fuel cycles development could be determined even now. In author's opinion the highest priority has the ENF plutonium cycle where plutonium is used as nuclear fuel to produce power and excessive neutrons which in its turn are directed toward transmutation of actinides and FPs.

It is explained by the availability of large stocks of power and weapon-grade plutonium with high power potential. In accordance with the decision of the Scientific and Technical Council of the RF Ministry of the Atomic Power Industry fast reactors are considered as the main nuclear and power facilities for utilization of the Russian weapon-grade plutonium. At the same time RF Ministry of the Atomic Power Industry supports the ENF development as an alternative line keeping in mind the possibility to operate the ENF blanket in a subcritical mode which increase the nuclear safety level in the event of its loading with weapon-grade plutonium. Hence the transmutation mode with power generation and use of the weapon-grade and power plutonium wherein plutonium FC with actinides and FPs as target materials is implemented has a priority in conducting promising R&D.

The second priority has a plutonium FC wherein the ENF operates in the mode of power generation and plutonium production of depleted uranium. The priority of this mode and FC is explained by the availability of large amounts of depleted uranium at storages of the nuclear nations. The involvement of depleted uranium makes it possible to increase the nuclear fuel resources substantially as resources of cheap natural uranium will be exhausted. All necessary technologies are available for this variant which are verified in industrial scale.

The third priority in author's opinion has a plutonium FC wherein the ENF operates in the mode of power generation and ^{233}U production of thorium. However, the involvement of ^{233}U into the FC implies the development of new technologies which will be necessary after all resources of natural uranium will be exhausted.

5. TRANSMUTATION PROCESS PECULIARITIES

The process of the FPs and actinides transmutation in neutron fluxes has its own peculiarities which has been taken into account in the ENF development. The FPs transformation is performed mainly by (n, γ)-reactions through sequential capture of neutrons being transmuted by a nuclide and formed by an intermediate nuclide. The destruction of actinides occurs mainly through fission reaction. Despite this difference the following HLW transmutation processes are characterized by the following parameters:

1. A_i - the actinides destruction rate which is determined by neutron flux density φ and σ_i, interaction effective cross-section.
2. The process power efficiency which is determined by the value of spent power for the destruction of one nucleus of the nuclide being transmuted or by a number of spent neutrons for the destruction of one nucleus.
3. The secondary radioactivity which is formed as a result of the HLW transmutation.
4. The value of the nuclides radiotoxicity before and after the transmutation.

Investigation of the mentioned above features allows to determine the list of nuclides which are advisable for transmutation. The short analysis of the mentioned above features is given below.

1. *A_i - destruction rate of nuclides being transmuted*

Since the value of A_i is proportional to $\varphi \cdot \sigma_i$, A_i for FPs will be the higher, the higher will be φ and σ_i values. The upper limit of φ which can be reached with present-day knowledge and experience is probably in the range of 5.10^{15}-10^{16} cm-^{2}·S^{-1}. The σ_i value depends on neutron spectrum. It is advisable to use thermal neutron spectrum for FPs transmutation through (n, γ)-reaction where cross-section follows the law of 1/V (V is the velocity of neutrons). Comparison of σ_i, effective cross-sections of actinides for fast reactors and ENF blanket thermal spectrum performed by ITEP scientists is tabulated in Tables 2 and 3 borrowed from [2]. It is seen from results given in Tables 2 and 3 that 6, effective cross-section of actinides in thermal spectrum is in most cases much higher than the same values for fast reactor.

ITEP specialists have estimated the value of the neutron flux density necessary for ^{90}Sr and ^{137}Cs [3] incineration. For ^{90}Sr the radiation capture cross-section accounts for $\sigma = 0.014$ barns according to the latest data (Einwei, 1983) or 0.0097 (Lone, 1993). According to older data it was believed that $\sigma = 0.9 + 0.5$ (Zets, 1966). If we are adhered to contemporary data and believe that $\sigma = 0.01$ barn, then neutron flux of $7.6 \cdot 10^{16}$cm^{-2}·S^{-1} is required for ^{90}Sr transmutation rate to be equal to its radioactive decay rate ($T_{1/2} = 28.8$ years). In this case the "half-destruction period" will be twice less than the half life, i. e. 15 years. For more rapid destruction higher flux densities (more than 10^{17} cm^{-2}·S^{-1}) would be required. Even though such flux densities could be achieved in ENF, it is unlikely that this will be economically justified.

For ^{137}Cs $\sigma = 0.11$ barn (Stupetta, 1960) or 0.25 barn (Harada, 1990). For transmutation rate to be equal to the radioactive decay rate ($T_{1/2} = 30$ years) the flux density of $6.7 \cdot 10^{15}$ or $2.9 \cdot 10^{15}$ cm^{-2}·S^{-1} is accordingly necessary which is achievable in modern reactors. In this case the "half-destruction period" will be 15 years. Flux densities higher than 10^{16} cm^{-2}·S^{-1} are required for more rapid destruction. It should be kept in mind that radiotoxicity of ^{90}Sr is significantly (37 times) higher than that of Cs137 (the maximum permissible concentration of ^{90}Sr in water is $4.0 \cdot 10^{-16}$ Ci/l, and that of ^{137}Cs is $1.5 \cdot 10^{-8}$ Ci/l). Therefore destruction of ^{137}Cs only without ^{90}Sr reduces initial radiotoxicity of ^{90}Sr + ^{137}Cs no more than 4% according to existing data on their interaction with neutrons.

2. *Transmutation process power efficiency*

It is quite obvious that power consumption for HLW destruction should be substantially less than amount of power generated by NPPs. According to investigations carried out by specialists from Moscow Physics Engineering Institute the FPs transmutation process is effective if power consumed for transmutation is appr. 30% of that generated in the NPP [4]. It is obvious that power balance in actinides destruction is positive. The power consumpt ion for HLW transmutation could be de termined after development of particular ENF design only. Therefore such characteristics as R_i, consumption of neutron necessary to destruct one FP's nuclei could be used for estimation of the power consumption. The R_i calculation results are tabulated in Table 4 [5]. It is evident from Table 4 that considerable amount of neutrons is required for transmutation of ^{93}Zr and ^{151}Sm. This demonstrates that their destruction in a neutron flux is ineffective from the power viewpoint. At the same time it is advisable to state a problem of their recycling in the FC. The transmutation of other radionuclides listed in the Table 4 is energetically advisable.

3. *Secondary radioactivity under transmutation*

The process of neutron generation for transmutation is accompanied by electric power consumption from external source for accelerator supply. If we believe that this electric power is generated in the NPP, then neutrons are produced as the result of fission reactions of the nuclear fuel in the reactor of the NPP which energize the accelerator. Moreover, nuclear reactions generating neutrons occur also in the blanket of the ENF itself. Hence the transmutation process, i.e. the process of one radioactivity unit destruction is accompanied by generation of FPs, that is secondary radioactivity. Because in the first 100 years after unloading of the NPP's spent nuclear fuel (SNF) its activity will be determined to appr. 90% by activity of ^{90}Sr and ^{137}Cs the secondary activity is mainly the activity of the medium-lived nuclides - ^{90}Sr and ^{137}Cs. The calculations of the secondary activity performed by ITEP specialists show that with elimination of all primary activity of the FPs (except for ^{90}Sr and ^{137}Cs) the secondary radioactivity is generated which accounts for 10-12% of the ^{90}Sr and ^{137}Cs primary radioactivity [5]. In the event of elimination of 100% of the primary activity including ^{90}Sr and ^{137}Cs the secondary activity is generated equal to 40% of the ^{90}Sr and ^{137}Cs primary activity. This result can be interpreted in the following way. First, the long-lived activity is transformed to a medium-lived with the help of an ENF. Second, we have to pay with generation of additional 10-12% of the secondary activity of the medium-lived ^{90}Sr and ^{137}Cs radionuclides ($T_{1/2}$ up to 30 years) for elimination of the total primary activlty of the long-lived FPs. This is a very serious result. It follows from this result that with the use of an ENF all long-lived FPs could be destructed. The cost of this is not too high. As for destruction of the medium-lived FPs, ^{137}Cs in particular, the ENF permits to decrease its amount 2-2.5 times compared with its initial content.

4. *Radiotoxicity*

The main radiobiological hazard represent actinides with high half lives. The relative indexes of toxicity, TI_i for long-lived actinides depending upon their storage time are tabulated in Table 5. TI_i is the amount of water required for dilution of the i nuclide up to a maximum permissible concentration. It is evident from Table 5 that the most radiation hazard in first 100 years represent ^{232}U, ^{244}CU, ^{238}Pu, ^{241}Am and ^{241}Pt (TI for ^{239}Pt is assumed to be equal to 1). After 1000 years some redistribution occurs: ^{241}Pu, ^{241}Am, ^{240}Pu, and ^{244}Cm come in the first place from radiation hazard point of view.

Taking into consideration high radiation hazard of actinides a comparison of the radiotoxicity has Deen performed for fuel loads of the thermal blanket, ENF, and fast blanket [2]. For comparison to be a representative one a stationary operation mode has been chosen such that the change in concentration of nuclides in the next cycle is the same as for the present one. The effective neutron flux density for fast reactor was assumed to be equal to $1.2 \cdot 10^{16}$ cm$^{-2}\cdot$S^{-1}, the effective cross-sections are listed in Table 2.

The cross-sections are listed in Table 3 for a thermal blanket, and effective, average over Maxwellian neutron spectrum neutron flux density was assumed to be equal to 5.10^{15} cm$^{-2}\cdot$S^{-1}. The results of TI values calculations are tabulated in Tables 6, 7, 8. The following conclusions could be made from these Tables:

1. The equilibrium mass of all actinides in the fast reactor stationary mode is 43 times higher than in thermal blanket.

2 The main contributions into actinides mass are made by:

^{237}Np (18%), ^{238}Pu (26%), ^{241}Am (15%), ^{242}cm (4%), ^{243}Cm (9%) in fast reactor;
^{237}Np (15%), ^{238}Pu (2.9%), ^{241}Am (4.9%), ^{242}Cm (37%), ^{244}Cm (16%), ^{246}Cm (13%) in thermal blanket.

3. The long-lived activity of actinides in fast reactor is 43 times higher than in thermal blanket. The long-lived activity in fast reactor is governed for 34% by ^{238}Pu and for 54% by ^{244}Cm, and for 90% by ^{244}Cm in thermal blanket.

4. TI_i, toxicity indexes for long-lived actinides in fast reactor is 140 times higher than in the ENF thermal blanket. The TI_i , the toxicity index corresponding to a stationary amount of long-lived actinides in fast reactor is 33 times higher than the toxicity index of actinides in its own annual replenishment. For thermal blanket the TI_{AC} is 4.3 times less than TI_{AC} in the annual replenishment. The results obtained demonstrate the ecological hazard of actinides transmutation in fast reactors and advantages of the ENF thermal blanket. Hence the reduction of actinides toxicity for several orders of magnitude occurs as the result of actinides transmutation in the ENF.

The mentioned analytical studies made it possible to chose FPs and actinides for transmutation. With consideration for the above mentioned characteristics it is advisable to transmute the following FPs and actinides: ^{79}Se, ^{99}Tc, ^{107}Pd, ^{126}Sn, ^{129}I; Np, Am, Cm, ^{232}U using plutonium for generation of excessive neutrons.

6. THE USE OF THE WEAPON-GRADE AND POWER PLUTONIUM IN ENF

The investigations carried out in ITEP and other institutions demonstrates that existent power reactors and reactors under development despite technical measures taken are not guaranteed from accidents of such class as accidents dealing with reactivity (accidents with a change in the core reactivity). The probability of the accident associated with reactivity increases when plutonium fuel is used in thermal reactors because the decline in safety parameters takes place. According to calculations performed by specialists from Physical Power Institute (Obninsk) for example the temperature and power coefficents of reactivity are increased in the WWER-500 reactor when MOX-fuel is used (4.8% and 2.7% instead of 3.6% and 2.1% respectively), the β_{eff} value is decreased (from $6.0 \cdot 10^{-3}$ to $4.4 \cdot 10^{-3}$ with a condition hold that efficiency of the operating groups of the CPS rods does not exceeds β_{eff}), the efficiency of the CPS rods is decreased by a factor of 1.3 [6].

The decline in nuclear safety level of fast reactors with Na coolant and plutonium fuel should be particularly emphasized. First, there is rather high error in determination of the breeding ratio and critical mass of fast reactors reaching 7-10% and 5% respectively. This situation leads to inaccuracy in the choice of the core volume (average power intensity) and reactivity margin between overloads. Second, the reactivity void coefficient for sodium (RVCS) could be positive. For instance, RVCS of BN-800 reactor was previously positive. To change the RVCS sign from positive to negative the BN-8OO reactor designers have excluded the upper and side shields. This method of solving the problem resulted in a decrease in the breeding ratio to 1 instead of 1.23.

The same disadvantage takes also place for Na fast reactors in the case of weapon-grade plutonium application.

The features of using weapon-grade and power plutonium in nuclear reactors are the following:

- part of delayed neutrons (β_{eff}) for Pu which is equal to $2.7\cdot10^{-3}$ is smaller than for U ($6.82\cdot10^{-3}$) and for WWER-1000 spent fuel with a burn-up of 40 kg/t ($4.37\cdot10^{-3}$);
- very high radiotoxicity of plutonium requires remote control technology of fuel management;
- small critical mass depending from plutonium isotope composition
- problem of the non-proliferation.

Addition of minor actinides to plutonium fuel for fast reactor with Na coolant leads to:

- decrease in β_{eff}, effective part of delayed neutrons;
- decrease in l_n average lifetime of prompt neutrons;
- positive reactivity void coefficient for Na.

The result is the decrease in safety level for a fast breeder.

These features of plutonium, especially of the weapon-grade one require special approach to the use of plutonium as nuclear fuel for atomic power industry.

In ITEP specialists' opinion the ENF operation with subcritical blanket permits to exclude accidents associated with reactivity and first of all such accident as reactor runaway on prompt neutrons. Therefore the ENF safety level is substantially higher than that of power reactors with a critical core. This fundamental advantage of the ENF gives grounds for use in ENF weapon-grade and power plutonium as nuclear fuel for power generation and excessive neutrons production.

ITEP experts have made analytical study of various alternatives of the ENF plutonium mode with power generation:

- weapon-grade plutonium burnout (Table 9);
- ^{237}Np transmutation (Table 10)
- ^{233}U production and transmutation of ^{99}Tc and ^{129}I (Table 11).

The results of these investigations have been presented at various international conferences, in particular at GLOBAL-93 conference in Seattle (USA) and ICENES-93 conference in Japan. It seems likely that they are well known to international scientific community. We would like to call attention to the possibilty of further increase in nuclear safety level through the ENF stationary operation mode (concerning burnout). This mode could be implemented through regular continuous replenishment by newly made fuel. The salient feature of this mode is the possibility to maintain the reactivity margin virtually at the unchanged level. And the fundamental matter is that burnout of ^{239}Pu and ^{241}Pu fissionable in thermal spectrum and increase in ^{240}Pu and ^{242}Pu portions occurs which results in impossibility to use plutonium for nuclear weapons production after its unloading from the ENF.

7. THE ENF STRUCTURAL DESIGN VERSIONS

There are two ENF versions:

- with horizontal blanket(s) and target(s)
- with vertical blanket(s) and target(s).

The proton beam could be a single one (the first version) or can be divided into several beams where each beam interacts with a single module (a module consists of a target and a blanket - the second version).

The target material could be solid (W for instance) or liquid (for example, Pb, Pb-Bi, molten salt). The target may have a window to divide plenums of the target and accelerator (the first version) or may have it not (the second version).

The blanket design may be of heterogeneous or homogeneous type with a thermal or fast neutron spectrum.

To provide the thermal neutron spectrum ITEP specialists are now in the process of investigation of heavy water as a moderator for two different versions:

- with a solid fuel and targets made of fission products and actinides and a heavy-water coolant (the same as "CANDU" heavy-water reactor) - a heterogeneous version. In this version application of target materials in liquid form in special curcuits that go through blanket so as to exclude the process of solid target manufacturing;
- with liquid fuel and targets made of materials such as nitrate salts dissolved in a heavy-water moderator - a homogeneous version.

ITEP specialists plan to investigate the possibility to use fluorine molten salts in future.

From the above versions the most preferential is the version with combined target and blanket wherein the problem of radiation resistance of walls separating target and blanket is excluded. ITEP specialists have developed in 1985 a combined target and blanket with Pb-Bi coolant and spherical fuel elements.

To provide fast neutron spectrum the specialists from PPI (Obninsk) investigate the possibility to use Pb-Bi coolant in the blanket.

At the present time the Design Bureau of Machine Building (N. Novgorod) is conducting study of various structural designs of the ENF. After finishing this study one ENF version could be chosen.

It should be pointed out that a solid fuel version is based on the verified technical approaches which increase the possibility of its implementation. A repeated radiochemical reprocessing of the solid fuel is necessary at the same time because of limitations on the fuel burnout value which rise the irretrievable losses during reprocessing. The liquid fuel version is deprived of this disadvantage, however rather complex technical problems of their own arise in this version.

Within recent years ITEP specialists suggested a number of interesting ideas, namely:

1. A double-purpose ENF consisting of two modules (each module involves an homogeneous blanket and a target) for power generation and transmutation of the HLW with liquid fuel proposed by Dr. B.R. Bergelson from ITEP. ^{238}U is loaded in one module to produce ^{239}Pu. ^{239}Pu producing actinides and FPs from power reactors are directed into the second module for power generation and incineration. A continuous chemical reprocessing of the circulated liquid fuel is performed in this case. The results of this study have been presented at the International Conference in Las Vegas in July 1994 [7].

2. Unique liquid fuel elements placed in the form of channel array in the ENF heavy-water moderator [8] are suggested by ITEP specialists Drs. V.D. Kazaritsy, V.R. Mladov et. al. for use in the ENF with a liquid fuel. The liquid fuel assembly design is shown in Fig. 1. As is seen in Fig. 1 there are two circuits inside a channel: a fuel circuit (a solution or suspension of powder in the heavy-water) and a circuit of the heavy-water coolant under pressure. The coolant serves to cool the fuel which circulates in the channel and leaves blanket for chemical reprocessing only. Part of the fuel composition is continuously extracted for reprocessing, fractionated and actinides are returned into fuel circuit and all the rest undergoes further processing: fractionation, storage, transmutation and disposal.

3. Application of a sectioned blanket with neutron valves which permits to rise the neutron muluplication in blanket and decrease requirements imposed on proton current [9].

8. TECHNICAL PROBLEMS OF THE ENF DEVELOPMENT. NEW TECHNOLOGIES

The blanket is the most complex unit of the ENF. Its complexity lies in the fact that high thermal neutron flux density equal to $5 \cdot 10^{15}$ $cm^{-2} \cdot S^{-1}$ and higher needs to be provided. Firstly, the possibility has to be found to rise the power generation density compared to those achieved in existing power reactors without decrease in reliability level. Secondly, there is a need in experimental substantiation of possibility to use section blanket with neutron valve without decrease in reliability level. Thirdly, in the case of use of the fuel and target material in liquid form the express technology of irradiated materials purification from non-metallic impurities needs to be developed. It is necessary to substantiate the radiation resistance of plutonium fuel with addition of minor actinides too. There is a need to check the possibility of the feasibility of the ENF accident protection from accelerator switch off signal.

In the case of initial target application the problem of membrane (window) development arises which divides the volumes of target and accelerator, has minimal proton absorption, must be manufactured of a heat-conducting material or has a cooling, must be remotedly replaced when a given neutron fluence is reached. It is expedient to study the possibility to abandon a separating membrane. This problem is however more complex than a problem of the membrane design development. The technology to purify the target material has to be developed too. To provide the acceptable power generation in target during interaction with proton beam two complex technical problems have to be solved:

1. to split the proton beam into several beams with lower intensity;
2. to widen the beam to the size needed.

Rather complex technical problems face the proton accelerator designers. One of these problems is a problem associated with development of a reliable RF accelerator power supply system. Existing 1 MW clystron generators with 60-70% efficiency have low service life and reliability. The second problem is to guarantee the required level of proton losses in various stages of their acceleration. According to calculations made in ITEP by Prof. Kapchinsky the beam losses have to account for appr. 10^{-6} of a nominal value. Specialists of ITEP and other institutes dealing with these problems believe that existing technical problems in the ENF development could be solved provided that means and efforts of specialists are concentrated on this.

9. R&D TO BE PERFORMED TO SUBSTANTIATE THE ENF FEASIBILITY

To substantiate the ENF feasibility a number of experimental investigations should be performed which verify the design parameters, safety level and reliability. The main design approaches for the following systems and technologies should be verified:

- blanket;
- target;
- accelerator;
- corntrol and protection system (CPS);
- technology of express purification of fuel and target materials in liquid state;
- technology of selective partitioning of FPs and actinides.

A tremendous work in nuclear data bases compiling should be done.

According to the decision of the Scientific & Technical Council of the RF Ministry of the Atomic Power Industry a R&D program for 1995-2000 is elaborated which makes provisions for works both with ENFs and fast reactors for incineration of actinides.

As for ENFs the following experimental works are incorporated in this program:

1. Modelling of different versions of a blanket with a 56 MeV proton accelerator driven subcritical assembly. For this purpose the program calls for construction of an experimental facility named "Transmutation neutron source" using the building and biological shielding of the HWR research heavy-water reactor. Berillium is supposed to be used as target material. Istra-36 experimental proton accelerator already existing in ITEP and tested at 200 mA pulse current will be used too.

The neutron source main goals are [9]:

- application as a full-scale physical model of the power transmutation facility blanket;
- check and improvement of the control and protection system for electro-nuclear complex;
- fundamental research (actinide constants for fast neutron parameters of proton interaction with blanket and accelerator materials, production of ultra-cold neutrons and use of them, etc.)

The neutron source will have the following parameters:

- proton energy, E_p	36 MeV
- proton pulse time, T_p	150 μs
- proton pulse current , I_p	150 mA
- mean proton current, I_p	0.5 μA
- proton pulse power, W_p	5.4 MW
- intensity of the target fast neutrons	$1.5 \cdot 10^{14}$ neutrons/s
- K of the start-up blanket	0.95
- start-up blanket power	25 kW
- thermal neutron flux reflection	$1.5 \cdot 10^{12}$ neutrons/$cm^2 \cdot S$
- start-up blanket load ^{235}U (90%)	2 kg

Commissioning of this facility will be determined by extent of funding which are scarce now.

2. Investigation of power generation in various targets as a result of interaction with protons, neutron and γ-quanta yields in spallation reactions, and reaction rates.

3. Investigation of cross-sections of the proton and neutron interaction with FPs and actinides (a number of Russian institutes are involved in this activity: Physical Power Institute, Radium Institute, All-Russian Research Institute of Experimental Physics, Institute of Theoretical and Experimental Physics).

4. Study of liquid target hydrodynamics on models.

5. Experimental verification of accelerator and some other units.

Pursuance of these research works allows to initiate the development of the ENF design not earlier than in 1998. At the same time the ENF feasibility study and construction site selection will be performed.

10. NON-PROLIFERATION PROBLEM

The problem of non-proliferation arises in the context of use of weapon-grade plutonium as nuclear fuel. This problem is determined by political, economical and technical considerations. Let us dwell on one technical aspect only relating to the requirement of impossibility to manufacture nuclear weapons from a stolen weapon-grade plutonium. There are two ideas which implementation allows in our opinion to prevent or at a last resort complicate weapon-grade plutonium theft considerably. The first idea is in mixing of ^{90}Sr and ^{137}Cs with weapon-grade plutonium and storage of this mixture in a storage. The fuel elements for loading into ENF blanket are then produced without separation of Cs and Sr from Pu. Because neutron capture cross-section of Cs and Sr are small their effect on neutron balance in blanket will be insignificant. It is obvious that first a mixing technology and second a technology of remote production of such fuel should be developed. If we manage to substantiate this idea for ENF, then a possibility to abandon purification of plutonium and some FPs with low absorption during the process of SNF reprocessing.

The second idea originally proposed by Prof. A.N. Shmelyov (Moscow Physical Engineering Institute) is that ^{237}Np is admixed to weapon-grade plutonium with further irradiation in the ENF's blanket. The Np content will rise with irradiation time of this type of fuel as a result of which plutonium contained in SNF will be unsuitable for nuclear weapon production. We propose to study these two ideas and hope to make some contribbution in solving this complex political problem using technical means.

We would like to dwell on one issue. In the case of MOX-fuel use in the ENF's blanket (i.e. the use of fuel with natural or depleted uranium) the possibility to produce weapon-grade plutonium could not be excluded. The similar note refers to existing and promising power reactors with MOX-fuel and to ENF operating mode used for plutonium production of depleted uranium.

11. PROPOSALS FOR INTERNATIONAL COOPERATION

In recent years for a variety of reasons a large number of experts in nuclear field were relieved of their duties in different nations. Part of them became involved in HLW transmutation and utilization of the weapon-grade and power plutonium.

In connection with this it is expedient to put for consideration as the first proposal to arrange an exchange of research reports on the themes discussed at this meeting.

The second proposal is to conduct scientific seminars and international conferences on themes discussed here systematically. In this respect the activity of the NEA/OECD which conducts the 3rd International Meeting should be supported. ITEP is ready to propose itself as a candidate for the 4th or 5th Information Meeting on the problem discussed to be held in Moscow in 1995-1996 provided that NEA will give its financial support. It would be useful to provide in the NEA pogram to conduct twice a year meetings of experts of different countries on some specific problems.

The third proposal is to prepare the international program on partitioning and transmutation. This would permit to coordinate the activity of scientists and specialists from various countries. In the case of positive attitude to this proposal ITEP is ready to submit the relevant proposal. ITEP believes that the problem discussed is of no less significance than an international project on thermonuclear synthesis. Should the NEA/OECD managed to unite the efforts of specilists from different nations in an international project this would be an exceptionally important political and technical decision. If this decision will find support, it is also advisable to consider the issue of organizing an international council to coordinate activity in this field.

The fourth proposal is to perform analytical studies of various versions of the ENF blanket and target including the problem of non-proliferation as important international problem including pursuance of calculations of various fuel compositions above.

The fifth proposal is to conduct experimental work to substantiate the ENF including measurements of nuclear constants study of physical and heat engineering features of the target blanket, accelerator, etc. In connection with this ITEP makes proposal to consider a possibility of the NEA/OECD and any other nation participation in funding of the "Transmutation Neutron Source' construction in ITEP and conducting the relevant physical experiments.

12. EXPECTED RESULTS

ITEP is of the opinion that analytical and experimental studies to be conducted in the next 4-5 years will make it possible to develop the design of the ENF which main purpose will be the safe power generation when using weapon-grade and power plutonium with concurrent transmutation of the part of the long-lived FPs and actinides. ITEP believes that international cooperation will permit to save material resoures and intellectual efforts of experts. It is seen even in this stage that as a result of this cooperation fundamentally new ideas and technologies could be implemented which are aimed at increasing the safety level of the nuclear power industry.

GENERAL CONCLUSION

1. Physical features of the transmutation process allow implementation of the HLW incineration in neutron flux using specialized nuclear facilities.

2. Electro-nuclear facilities are preferable than fast reactors due to high level of nuclear safety, lower radiotoxicity of minor actinides and a possibility to close the nuclear fuel cycle as to fissionable materials and fission products.

3. International cooperation of specialists from various nations to develop and construct the electro-nuclear facility is necessary.

List of Tables

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Table 1. Radioactive waste in Russia

Radioactive waste from different industries	Liquid m^3/Ci	Solid m^3/Ci	Vitrified m^3/Ci	Other
1. Ministry of the Atomic Power Industry of the Russian Federation	$56\cdot10^6$/ $6\cdot10^5$	-	-	
1.1 Uranium mines				
1.2 Production of UO_2, uranium enrichment, fuel manufacturing	$1.6\cdot10^6$/ $9.3\cdot10^4$	-	-	
1.3 Reprocessing of the NPPs spent fuel	$416\cdot10^6$/ $2.65\cdot10^9$	-	250t glass/ $25\cdot10^6$	*)
- storage in tanks	/$570\cdot10^6$	-	-	
- storage in ponds	/$700\cdot10^6$	-	-	
- solid radioactive waste storage	-	/$12\cdot10^6$	-	
1.4 NPPs	$1.5\cdot10^5$/ $3.5\cdot10^4$	$1.0\cdot10^5$/	$12\cdot10^4$/	**)
2. Shipbuilding	$1.2\cdot10^3$/ $2.5\cdot10^2$	$1.9\cdot10^5$/	-	***)
3. Civilian ships	10^3/ 10^1	$5.2\cdot10^2$/	-	
4. Research institutes, hospitals, etc.	-	$7.5\cdot10^3$/ $8\cdot10^5$	-	

*) 1000 t of the WWER spent fuel
**) 5325 t of the NPPs spent fuel at site
***) 15 spent cores with $15\cdot10^6$ Ci

Table 2. σ_r, σ_f, σ effective cross-sections and ν, the number of secondary neutrons for fast reactor

Nuclide i	σ_r, b	σ_f, b	σ, b	ν, neutrons/fission
^{237}Np	1.4	0.3	1.7	2.9
^{238}Pu	0.5	1.1	1.6	3.0
^{239}Pu	0.5	1.8	2.3	2.9
^{240}Pu	0.5	0.4	0.9	3.1
^{241}Pu	0.4	2.4	2.8	3.0
^{242}Pu	0.4	0.3	0.7	3.0
^{241}Am	1.7	0.3	2.0	3.4
^{242m}Am	0.4	3.2	3.6	3.2
^{243}Am	1.0	0.2	1.2	3.6
^{242}Cm	0.288	0.185	0.473	3.5
^{243}Cm	0.3	2.6	2.9	3.8
^{244}Cm	0.6	0.4	1.0	3.5
^{245}Cm	0.4	2.8	3.2	3.8
^{246}Cm	0.77	0.47	1.24	3.5

Table 3. σ_r, σ_f, σ effective cross-sections and ν, the number of secondary neutrons for thermal reactor

Nuclide i	$T_{1/2}$, yrs	σ_r, b	σ_f, b	σ, b	$\nu^{*)}$ neutr/fiss
^{237}Np	2.14+6	203.4	0.706	204.1	2.25
^{238}Np	2.117 days	62	1773	1835	2.8
^{239}Np	2.355 days	67.5	-	67.5	-
^{238}Pu	87.71	433	17.1	450	2.9
^{239}Pu	2.41+4	268	666	934	2.877
^{240}Pu	6569	1050	0.93	1051	-
^{241}Pu	14.35	316	910	1226	2.937
^{242}Pu	3.76+5	126	0.7	12.7	-
^{243}Pu	4.956 hrs	97	213	310	-
^{241}Am	432.6	540	4.01	544	3.21
^{242g}Am	16.1 hrs	-	1725	1725	3.26
^{242m}Am	141	1637	6372	8009	3.26
^{243}Am	7348	243	1.16	244	-
^{244}Am	10.1 hrs	-	1856	1856	-
^{244m}Am	26 min	-	1291	1291	-
^{242}Cm	161.4 days	23.0	< 4	27	-
^{243}Cm	28.5	657	127	784	3.43
^{244}Cm	18.1	77.2	2.63	79.9	-
^{245}Cm	8.5+3	292	1735	2027	3.717
^{246}Cm	4.7+3	13.1	1.13	14.2	-
^{247}Cm	1.56+3	99	142	241	-
^{248}Cm	3.4+5	29.1	1.8	31	-
^{249}Cm	64.15 min	1.3	-	1.3	-
^{249}Bk	329 days	995	-	995	-

*) For nuclides which have no ν data the following values were assumed: ^{242}Pu, ^{243}Pu - 3.0; ^{243}Am, ^{244}Am, ^{244m}Am, ^{242}Pu - 3.3; ^{244}Cm - 3.5; ^{245}Cm , ^{247}Cm - 3.8; ^{248}Cm - 3.9

Table 4. Neutron consumption for the FPs transmutation

Nuclide i	$T_{1/2}$, years	γ_i	R_i
^{90}Sr	28.8	5.94-2	2
^{137}Cs	30.17	6.23-2	3
^{151}Sm	93	4.16-3	30-250
^{99}Tc	2.14+5	6.15-2	1.15-1.5
^{93}Zr	1.5+6	6.35-2	150
^{126}Sn	1.0+5	5.72-4	
^{79}Se	6.5+4	4.49-4	1.5
^{135}Cs	3.3+6	6.55-2	
^{107}Pd	6.5+6	1.42-3	
^{129}I	1.6+7	7.68-3	2

Note: The entry of 5.94-2 type means $5.94 \cdot 10^{-2}$ and 1.5+6 means $1.5 \cdot 10^{+6}$.

Table 5. Secondary radioactivity in incineration of nuclides contained in 1 tonne of the WWER-1000 spent nuclear fuel

Nuclide i	m_i, g/t	$m_i Q_i^{(0)}$, Ci/t	$m_i Q_i^{(2)}$, Ci/t	$m_i Q_i^{(2)}$, Ci/t
^{90}Sr	678	9.4+4	2.2+4	4.3+4
^{137}Cs	1460	1.3+5	4.8+4	9.1+4
^{151}Sm	14.9	405	(4.5+3)-(2.2+4)	(0.75-7.0)+4
^{99}Mo	950	16.2	2.0+6	4.0+6
^{93}Zr	907	2.3		
^{126}Sn	22.4	0.64		
^{79}Se	5.9	0.41	165	320
^{135}Cs	422	0.486		
^{107}Pd	254	0.13		
^{129}I	220	0.039	5.0+3	9.7+3
Total without Zr, Sm		2.4+5	9.2+4	1.7+5
Without Zr, Sm, Cs, Sr			(2.1-2.7)+4	(4.1-5.1)+4

Note: The secondary radioactivity $m_i Q_i^{(2)}$ is caused basically by ^{90}Sr and ^{137}Cs.

Table 6. Characterisitics of fast reactor stationary mode

Nuclide i	x_i, nuclei	M_i, kg	q_i, Ci	TI_i, l of water
^{237}Np	6.91+25	27.2	19.2	1.28+9
^{238}Pu	1.0+26	39.7	6.84+5	2.74+15
^{239}Pu	2.17+25	8.63	535	2.43+12
^{240}Pu	1.57+25	6.26	1421	6.46+12
^{241}Pu	2.68+24	1.07	1.11+5	1.01+13
^{242}Pu	2.29+25	9.19	36.1	1.51+11
^{241}Am	5.75+25	23.0	7.89+4	8.32+13
^{242m}Am	2.72+24	1.09	1.15+4	1.04+13
^{243}Am	2.70+25	10.9	2182	1.98+12
^{242}Cm	1.58+25	6.35	2.12+7	3.54+15
^{243}Cm	1.60+24	0.646	3.33+4	2.66+13
^{244}Cm	3.31+25	13.4	1.08+6	6.02+14
^{245}Cm	6.21+24	2.53	433	5.10+11
^{246}Cm	2.0+24	0.817	251	2.80+11

Table 7. Characterisitics of thermal reactor stationary mode

Nuclide i	x_i, nuclei	M_i, kg	q_i, Ci	TI_i, l of water
^{237}Np	1.36+24	0.536	0.379	2.53+7
^{238}Np	1.09+23	0.043	1.12+7	1.12+15
^{239}	8.94+21	0.0036	8.24+5	1.12+12
^{238}Pu	2.58+23	0.102	1764	7.06+12
^{239}Pu	1.26+23	0.050	3.11	1.41+10
^{240}	3.21+22	0.0128	3.08	1.73+10
^{241}Pu	2.75+22	0.011	1137	1.03+11
^{242}Pu	2.61+23	0.105	0.412	1.72+9
^{243}Pu	4.09+21	0.016	4.30+6	1.26+14
^{241}Am	4.30+23	0.172	590	6.22+11
^{242g}Am	5.97+22	0.024	1.94+7	2.98+14
^{242m}Am	3.53+21	1.42+3	14.9	1.35+10
^{243}Am	3.72+23	0.150	30.1	2.74+10
^{244}Am	8.2+20	0.0003	4.23+5	1.76+11
^{244m}Am	9.5+20	0.004	1.14+7	4.74+12
^{242}Cm	3.21+24	1.29	4.31+6	7.18+14
^{243}Cm	9.44+22	0.0381	1967	1.57+12
^{244}Cm	1.38+24	0.559	4.51+4	2.50+13
^{245}Cm	5.50+22	0.0224	3.84	4.52+9
^{246}Cm	1.14+24	0.465	143	1.59+11
^{247}Cm	6.17+22	0.0253	2.35-3	-
^{248}Cm	1.97+23	0.0812	0.344	3.12+8
^{249}Cm	1.6+20	6.6-5	7.78+5	6.76+11
^{249}Bk	5.8+21	1.83-4	3825	2.54+10

Table 8. Characterisitics of fast and thermal high-flux reactor stationary mode

Characteristics	Fast reactor	Thermal reactor	$\frac{\text{Fast}}{\text{Thermal}}$
M, kg	151	3.52	43
q_{sl}, kg	6.34+7	4.57+7	1.4
q_{ml}, kg	2.12+7	4.31+6	4.9
q_{ll}, kg	2.00+6	5.00+4	40
TI_{sl}, l HO	3.67+15	1.31+15	2.8
TI_{ml}, l Ho	3.53+15	7.18+14	4.9
TI_{ll}, l HO	3.48+15	2.46+13	140
$M_{replen.}$, kg/yr	39.2	39.2	
$q_{replen.}$, Ci/yr	1.32+5	1.32+5	
$TI_{replen.}$, l/yr	1.04+14	1.04+14	
$q_{unload.\ ll}$, Ci/yr	1.7+5	1.7+5	
$TI_{unload.\ ll}$, l/yr	1.1+14	1.14+14	

M - total nuclide mass;

q_{sl} - total short-lived activity determined by short-lived nuclides with half life less than appr. 2 days (^{238}Np, ^{239}Np, ^{243}Pu, ^{244g}Am, ^{244}Am);

q_{ml} - medium-lived activity determined by ^{242}Cm with half life $T_{1/2}$ = 161.4 days;

q_{ll} - long-lived activity determined by other long-lived nuclides;

TI_{sl}, TI_{ml}, TI_{ll} - toxicity indexes for these 3 nuclide groups;

$M_{replen.}$ - total mass of actinides being replenished per year;

$q_{replen.}$ - total activity of the annual replenishment;

$TI_{replen.}$ - total toxicity index of the annual replenishment;

$q_{unload.\ ll}$ - total activity of ^{90}Sr and ^{137}Cs (in this case nuclide yields were assumed 2.2% for ^{90}Sr and 6.8% for ^{137}Cs) removed in one year from fission products produced in stationary mode;

$TI_{unload.\ ll}$ - their toxicity index.

Table 9. Blanket performance data for weapon-grade Pu.

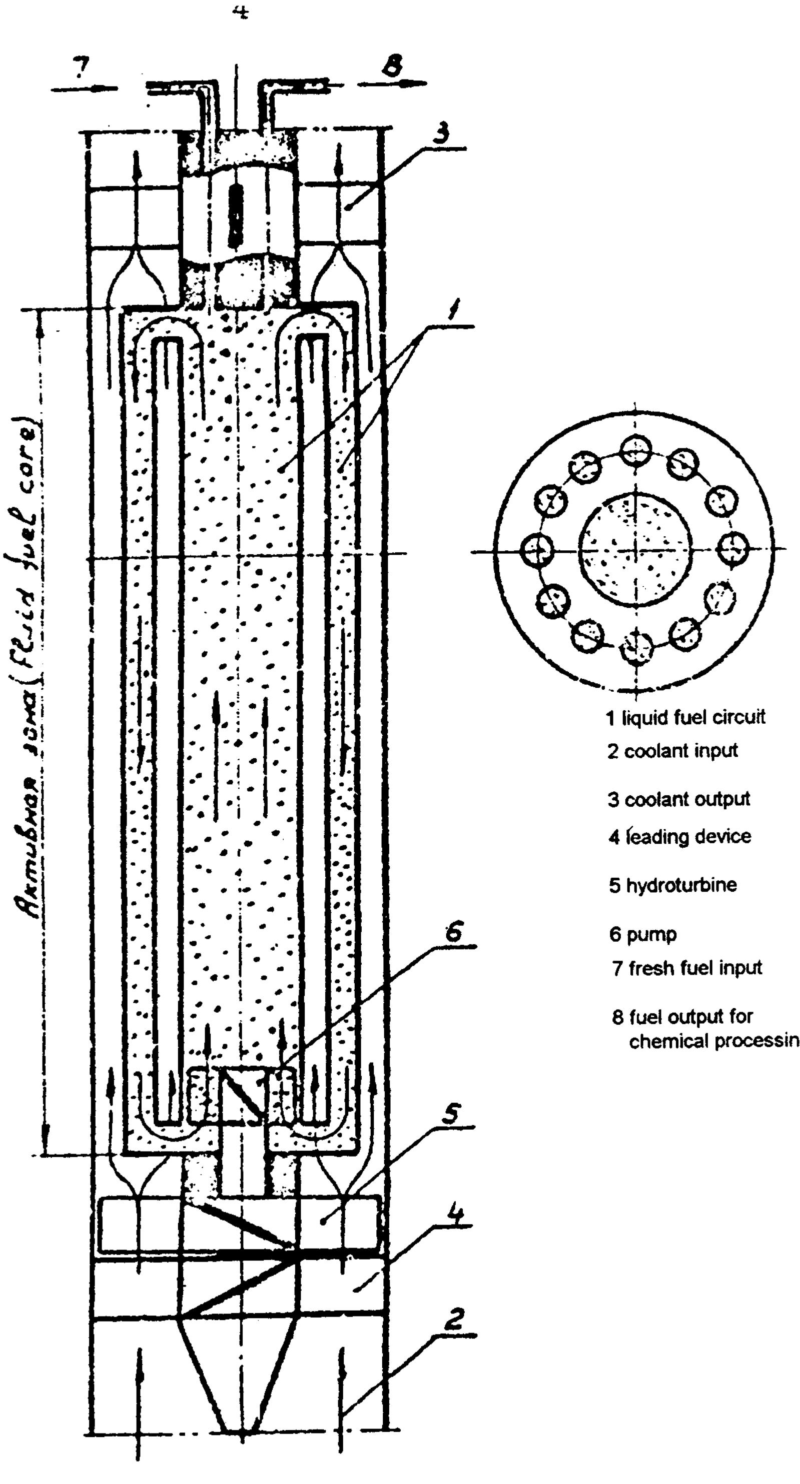
ENR thermal power	2200 MW
ENR electrical power	680 MW
Linac electrical power	100 MW
Coolant pressure	10 MPa
Coolant temperature	
input	226° C
output	310° C
Number of linacs	1
Number of target and blanket modules	2
Proton beam power	30-60 MW
Proton energy	800 MeV
Proton current	28 mA
Target:	
material (solid target)	Cu or W
cylinder size	3000 x 6000 mm
Neutron source intensity	$3 \cdot 10^{18}$ neutrons/s
Power density in target	30 MW
Multiplication factor, k	0.97
Blanket factor	1100 MW
Mode of the fuel replenishment	continuous
Number of channels in blanket	380
Lattice pitch	280 mm
Weapon-grade plutonium consumption	850 kg/year

Table 10. ENF main performance data for ^{237}Np transmutation

ACCELERATOR	
proton energy	1.6 GeV
proton current	0.3 A
TARGET	
inside diameter	0.38 m
material	Pb
proton to neutron conversion ratio	50 neutrons/proton
neutron source intensity	$9.36 \cdot 10^{19}$ neutrons/s
BLANKET	
thermal power	1.8 GW
core height	2.5 m
diameter of the core with Np	2.12 m
multiplication factor, k	0.598-0.572
thermal neutron flux density	$3 \cdot 10^{15}$ $cm^{-2} \cdot s^{-1}$
Np incineration rate	484.6 kg/year

Table 11. Performance data of the ENF modules

TARGET	
material	Pb
BLANKET	
height	2.5 m
diameter (with reflector)	5 m
type of assemblies	CANDU with pressure tubes
number of assemblies	250
pressure tube size:	
inside tube radius	5.42/5 cm
outside tube radius	6.23/5.81 cm
pitch (hexagonal lattice)	23.8 cm
tube material	Zr - Nb
moderator	D_2O with dissolved nitrite salts, Tc, Th
Module thermal power	1800 MW
Module electric power	600 MW
ENF life cycle	30 years
Pu initial load in each module	305 kg
Subcriticality level	0.97 - 0.98
Pu consumption in 30 years	100 tonnes
^{233}U production in 30 years	78 tonnes
Transmutation of ^{99}Tc, ^{129}I, and partially of Sm from ENF	



1 liquid fuel circuit
2 coolant input
3 coolant output
4 leading device
5 hydroturbine
6 pump
7 fresh fuel input
8 fuel output for chemical processing

Fig. 1 Principle diagram of the liquid fuel element