Physics – Uspekhi **47** (12) 1221 – 1237 (2004)

INSTRUMENTS AND METHODS OF INVESTIGATION PACS numbers: **25.20. – x**, 25.85.Jg, **28.41. – i**

Electrophotonuclear energy cycle

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DOI: 10.1070/PU2004v047n12ABEH001941

Contents

Abstract. It is shown that the current problems related to the nuclear power cycle can be resolved if the conventional fission process is complemented with the 'photoneutron reprocessing' of fissile nuclei directly in spent uranium by using the energy of relativistic storage-ring electrons and transforming it to synchrotron/undulator gamma radiation, and by utilizing the fission products as neutron sources while at the same time transmuting them into stable isotopes. A suitable method of 'gamma – neutron transmutation' is described, and the values of its parameters that make the corresponding 'electrophotonuclear' power cycle closed and waste-free are determined.

"*I would like to ... set the priorities. I believe that first we must close the fuel cycle...*"
Hans Bethe [1]

1. Introduction

As an innovation of the second half of the 20th century, the nuclear power industry could have had (but still does not have) well-defined prospects of development that would have been widely acknowledged by society. The dangers presented by radioactive waste, the threat of proliferation of fissile materials, and wastefulness in the use of natural uranium — all these factors are among the problems that must be solved because there is simply no alternative to nuclear power.

These problems were resulted from the spontaneously formed structure of the nuclear power cycle now in use, according to which at its back end the spent nuclear fuel (SNF) is held up in storages for 50 years, then encapsulated, and buried or after being held up for 10 years in the nuclear power plant (NPP) storage is transported for processing. The last process amounts only to radiochemical regeneration of the spent uranium — that is, (A) Pu is extracted and minor actinides (Np, Am, and Cm) and fission products are separated, with the latter classified as high radioactive waste (HRW); (B) the HRWs are immobilized (for example, are vitrified); (C) then they are stored for 50 years in terrestrial conditions, and (D) are, finally, buried in geological formations [2]. The extracted (power-generating) plutonium and the regenerated uranium are sent to a storage facility, so that in the future they can be used to produce mixed U – Pu fuel. The diagram of such an open nuclear fuel cycle is shown in Fig. 1.

The utilization of power-generating plutonium as the fissile component in U – Pu fuel is hindered by the nonoptimal isotopic composition, by the need to accumulate and store plutonium for a long time, and, primarily, by the dangers associated with the handling of plutonium in open form and the dangers of uncontrollable proliferation. Hence, today only 10 – 15% of unloaded SNF is processed, while the remainder is sent for prolonged storage and direct burial, which means that each year the amount of uranium withdrawn from circulation increases by 10 000 – 12 000 tons [2].

At present, the total nuclear power output of all the countries in the world is about 400 GW (el.) [3]. For later discussion, it is convenient to consider it as being generated by 400 conventional NPP units with water-moderated water-cooled power reactors of the VVR-1000 type. When a unit of this kind operates for a time commensurable with or exceeding the lifetime τ_i of the ith radioactive nuclide, the total number of nuclei of the radioactive nuclide in the unreprocessed SNF and HRWs reaches an asymptotically equilibrium value N_{0i} which can be determined from the equilibrium condition

$$\frac{\mathrm{d}N_i}{\mathrm{d}t} = \dot{S}_i - \lambda_i N_i = 0\,, \qquad (1)$$

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Received 8 June 2004, revised 29 September 2004
Uspekhi Fizicheskikh Nauk **174** (12) 1319 – 1335 (2004)
Translated by E Yankovsky; edited by A Radzig

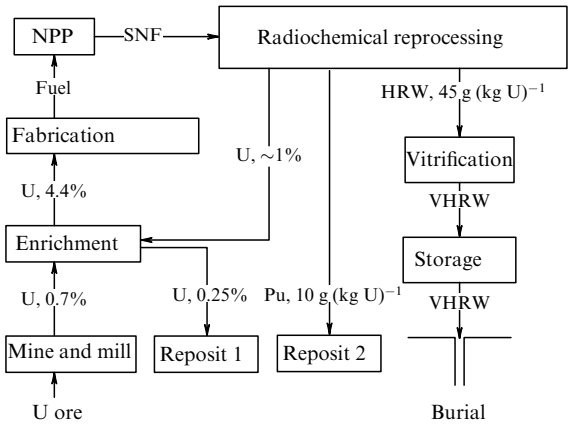

Figure 1. Flow chart for an open nuclear power cycle. For U, the enrichment is in the ^{235}U isotope, and the content of Pu and HRW is that in SNF of VVR-1000 reactors (FA, fuel assembly; VHRW, vitrified HRW).

where N_i and $\dot{S}_i$ are the number of nuclei of the ith radioactive nuclide and the rate of their accumulation in the unit's fuel, respectively, and $\lambda_i = 1/\tau_i = \ln 2/T_{i\,1/2}$ is the nuclide's decay constant. This condition yields

$$N_{0i} = \dot{S}_i \tau_i \,. \tag{2}$$

The rate of accumulation of the nuclei of the ith nuclide in the unit's fuel can be defined as the average over the campaign period T_c:

$$\dot{S}_i = \frac{N_i}{T_c} \,, \tag{3}$$

where N_i is the number of nuclei of the nuclide in the fuel at the time of fuel unloading.

According to equations (2) and (3), the equilibrium number of nuclei of the ith radioactive nuclide and the equilibrium activity A_{0i} of the nuclide are given by the following formulas

$$N_{0i} = N_i \frac{\tau_i}{T_c} \,, \quad A_{0i} = \lambda_i N_{0i} = \frac{N_i}{T_c} \,. \tag{4}$$

Below we present the results of calculations of the partial activity and radiotoxicity[1] of the fission radionuclides (FRs) and transuranium actinides (TAs) produced by an NPP 1-GW (el.) unit in the course of a time interval equal to the lifetime of the main fission radionuclides ^{90}Sr and ^{137}Cs, which roughly amounts to 42 years. Tables 1 and 3 list the equilibrium values of the above quantities for nuclides with half-lives $T_{1/2} \leqslant 30$ years, while Tables 2 and 4 list the values of the activity and radiotoxicity for long-lived nuclides (with half-lives $T_{1/2} > 30$ years) that linearly accumulate during the unit's campaign period mentioned. The calculations were done for the VVR-1000 reactor with the following standard parameters: fuel enrichment in ^{235}U, 4.4%; fuel burn-up, 40 GW day t^{-1}; mass of ^{238}U, 66 t, and campaign period $T_c = 875$ days. We have adopted the following notation in the tables: q_i is the mass yield of the ith nuclide per ton of ^{238}U, q'_i is the yield of the ith nuclide per unit thermal energy output, Q_i and A_i are the mass and activity of the ith nuclide, respectively, while $\mathrm{Rt}_i^{\mathrm{w}}$ and $\mathrm{Rt}_i^{\mathrm{a}}$ are the radiotoxicities of the ith nuclide with respect to water and air, respectively (in determining these radiotoxicities, MPC values set by the radiation safety standards NRB-96 were used), FR is a fission radionuclide, and TA is a transuranium actinide.

[1] The radiotoxicity of a nuclide is defined as the ratio of the radioactivity of the nuclide to the maximum permissible concentration (MPC) value for the respective medium (water or air) and has the dimensions of volume.

Table 1. Equilibrium activity of radionuclides with $T_{1/2} \leqslant 30$ years in the SNF from a 1-GW (el.) unit.

Parameter	^{95}Nb – ^{144}Ce	^{90}Sr	^{137}Cs	$\sum_{\mathrm{FRs}}$	^{236}Pu – ^{242}Cm	^{241}Pu	^{243}Cm	^{244}Cm	$\sum_{\mathrm{TA}}$
$T_{1/2}$, year	$\leqslant 10$	28.5	30.2	—	< 3	14.5	28.5	18.1	—
q_i, g t^{-1}	903	681	1476	3060	125	1577	0.45	31.2	1734
q'_i, g (GW day)$^{-1}$	22.7	17.1	37.0	76.8	3.12	39.4	0.01	0.78	43.3
Q_{0i}, kg	42.2	786	1762	2590	0.32	897	0.51	22.3	920
A_{0i}, MCi	166	215	306	687	7.62	98.5	0.03	1.81	108

Table 2. Activity of radionuclides with $T_{1/2} > 30$ years in the SNF from a unit with an output power of 1 GW (el.).

Parameter	$\sum_{\mathrm{FRs}}$	^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	^{242}Pu	^{241}Am	^{243}Am	$\sum_{\mathrm{TA}}$
$T_{1/2}$, year	—	2.14×10^6	87.8	2.41×10^4	6537	3.76×10^5	433	7380	—
q_i, g t^{-1}	3254	561	178	6335	2405	626	34.7	126	10266
q'_i, g (GW day)$^{-1}$	81.8	14.0	4.45	158	60.1	15.6	0.87	3.15	256
Q_{1i}, kg	3720	645	204	7282	2764	720	39.9	145	11800
A_{1i}, kCi	7.90	0.91	3493	453	632	2.84	137	57.6	4776

Table 3. Equilibrium radiotoxicity of nuclides with $T_{1/2} \leqslant 30$ years in the SNF from a 1-GW (el.) unit.

Parameter	^{95}Nb – ^{144}Ce	^{90}Sr	^{137}Cs	$\sum_{\mathrm{FRs}}$	^{236}Pu – ^{242}Cm	^{241}Pu	^{243}Cm	^{244}Cm	$\sum_{\mathrm{TA}}$
$\mathrm{MPC_w}$, kCi km^{-3}	1.5–57	1.2	2.6	—	2.6 – 43	7.3	0.17	0.21	—
$\mathrm{Rt}_{0i}^{\mathrm{w}}$, 10^3 km^3	16.8	98.3	58.9	174	0.52	48.0	0.18	8.62	57.3
$\mathrm{MPC_a}$, mCi km^{-3}	75 – 3800	150	780	—	0.76 – 4000	4.32	0.10	0.12	—
$\mathrm{Rt}_{0i}^{\mathrm{a}}$, 10^9 km^3	0.64	0.76	0.20	1.60	1.28	84.7	0.32	15.6	102

Table 4. Radiotoxicity of nuclides with $T_{1/2} > 30$ years in the SNF from a 1-GW (el.) unit.

Parameter	$\sum_{FRs}$	^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	^{242}Pu	^{241}Am	^{243}Am	$\sum_{TA}$
MPC_w, kCi km^{-3}	—	0.3	0.15	0.14	0.14	0.14	0.17	0.17	—
Rt_{li}^{w}, 10^3 km^3	4×10^{-4}	0.002	23.3	3.24	4.51	0.02	0.81	0.17	32.0
MPC_a, mCi km^{-3}	—	0.176	0.086	0.078	0.078	0.081	0.095	0.095	—
Rt_{li}^{a}, 10^9 km^3	2×10^{-5}	0.003	40.6	5.81	8.10	0.035	1.44	0.30	56.3

Table 5. Total activity and radiotoxicity of equilibrium (E) and linearly accumulating (L) nuclides produced by a VVR-1000 reactor in a lifetime of the main fission products ^{90}Sr and ^{137}Cs.

Parameter	Equilibrium nuclides			Linear nuclides			Sum E + L
	FR	TA	FR + TA	FR	TA	FR + TA	
Q, t	2.59	0.92	3.51	3.72	11.8	15.5	19.0
A, MCi	687	108	795	0.008	4.78	4.79	800
Rt_w, 10^3 km^3	174	57.3	231	$< 10^{-3}$	32.0	32.0	263
Rt_a, 10^9 km^3	1.60	102	104	$< 10^{-4}$	56.3	56.3	160

The column in Table 1 for fission radionuclides with $T_{1/2} \leqslant 10$ years lists the total contributions from ^{85}Kr, ^{89}Sr, ^{95}Nb, ^{95}Zr, ^{106}Ru, ^{125}Sb, ^{131}I, ^{133}Xe, ^{134}Cs, ^{136}Cs, and ^{144}Ce isotopes. For ^{90}Sr and ^{137}Cs, as well as for ^{95}Zr, ^{106}Ru, and ^{144}Ce isotopes, the activity of the products of their beta decay was taken into account. In the column for transuranium actinides with $T_{1/2} < 3$ years, the total contribution from ^{236}Pu, ^{238}Np, and ^{242}Cm isotopes is listed. In the case of ^{241}Pu, the activity of ^{241}Am, which accumulates because of the beta decay of the former, was taken into account. The second column in Table 2 gives the total contributions from the long-lived fission radionuclides ^{93}Zr, ^{99}Tc, ^{107}Pd, ^{129}I, and ^{135}Cs ($T_{1/2} > 1.5 \times 10^6$ years). In the case of ^{93}Zr, the activity of the long-lived isomeric state of its daughter ^{93}Nb nucleus was taken into account, while in the case of ^{237}Np, the activity of its daughter ^{233}Pa nucleus was taken into account.

The data listed in the tables imply that when an NPP operates in equilibrium conditions between the numbers of produced and decaying short- and medium-lived radionuclides, the main contribution to the total equilibrium activity of the unprocessed SNF and the separated HRW is provided by ^{90}Sr and ^{137}Cs nuclides. These nuclides also represent the greatest danger in the contamination of soil and water, since their radiotoxicity accounts for 70% of the total radiotoxicity of nuclides with $T_{1/2} \geqslant 30$ years. ^{137}Cs isotope also provides the largest contribution to the dose level of the external radiation. The isotopes of plutonium and minority actinides fully determine the radiotoxicity with respect to air and, therefore, present the greatest danger in propagating via the air – aerosol route.

Tables 1 – 5 clearly demonstrate that the total equilibrium activity generated by all the stationary NPP units, mobile nuclear power plants, and industrial and research reactors that are currently in operation can be estimated at roughly 350×10^9 Ci. This value is expected to be reached in the first 40 to 50 years of operation of all nuclear power-generating units, which amounts to roughly the lifetime of the main 'equilibrium' radionuclides ^{90}Sr and ^{137}Cs. After that, the value will gradually increase in the course of operation of the nuclear facilities due to the accumulation of the above-mentioned long-lived (linear) radionuclides. These results were obtained on the basis of reference data (see Ref. [4]) and make it possible to assess the constantly acting factors of radiation-associated risks that will emerge as a result of the operation of all the nuclear power-generating units in the world at the current power output by 2020 – 2025 if the process of accumulation of unprocessed SNF and HRW is not stopped.

The radiotoxicity with respect to water, determined almost entirely by ^{90}Sr and ^{137}Cs nuclides, will amount to about 1.1×10^8 km^3, which is roughly 8% of the total volume of the oceans. The radiotoxicity of the isotopes of plutonium and minority actinides that will be produced only in the first 40 to 50 years of operation of the world's nuclear power-generating units at the current power output will amount to approximately 6.5×10^{13} km^3 of air, which is larger than the volume of the earth's atmosphere by a factor of 1000. In energy release, the produced equilibrium activity is equivalent to approximately 0.1% of the activity of natural ^{238}U, ^{232}Th, and the families of their daughter radionuclides, which are contained in the earth's crust and to a large extent determine the crust's temperature.

For a long time after a nuclear power facility is decommissioned, the fraction of the partial contributions of the above groups of radionuclides in the total amount of activity and radiotoxicity remains close to the above-presented value. In the first 200 years after the facility has stopped operating (or the SNF is unloaded from an operating facility), ^{90}Sr and ^{137}Cs nuclides continue to provide the main contribution to the total activity. The same elements determine in this time interval the radiotoxicity with respect to water and the dose level of the external radiation.

Of the transuranium actinides, the main contribution to the total alpha activity in the above-mentioned time interval is provided by the ^{241}Am isotope, produced in the beta decay of ^{241}Pu. The radiotoxicity of actinides with respect to air remains almost the same with the passage of time (in 500 years it decreases by a factor of only two), with the result that actinides form the chief risk factor of propagating via the air – aerosol route in the foreseeable future.

The above data imply that

(1) the burial of unprocessed SNF and HRW in geological formations, inevitable in the case of an open nuclear power cycle, is dangerous because it does not exclude the risk of the above-mentioned highly toxic radionuclides spreading in the environment and of uncontrollable growing of underground energy release in the burial grounds. The latter could lead to unpredictable and irreversible thermoecological consequences;

(2) full-scale terrestrial storage of unprocessed SNF and HRW would require building new large storage facilities, but instead of reducing the above risks such an approach would only add the risk of contaminating (irradiating) microflora and microfauna, which may lead to unpredictable bioecological consequences. If we assume that SNF must be stored in terrestrial conditions for at least 200 – 250 years, i.e., for a period long enough for the activity and radiotoxicity with respect to water of the fission products to be reduced to levels characteristic of transuranium actinides, then storage facilities would have to be built with storage areas twice as large as those that are presently used at existing nuclear power facilities, since the standard fuel burn-up at nuclear power facilities in reactors of the VVR type is achieved in 2.5 years. These storage facilities would have to be maintained, serviced, and guarded during the entire period of operation of the objects of nuclear power industry, and even after removing such objects from service they would have to operate for a prolonged time period comparable to that mentioned above;

(3) accumulation of the products of radiochemical SNF processing increases the danger of the uncontrollable spread of plutonium and highly toxic fission products. The associated risks, which are the products of many factors, increase with time nonlinearly. In view of the unlimited nature of the use of atomic energy, the design limits of safe storage of the above radionuclides sooner or later will be exceeded and the risks will become critical.

The aforesaid implies that with the contemporary nuclear power cycle the above-mentioned risks are conserved for the entire operational time of a nuclear power facility and for several hundred years after its operation has ceased. The risks cannot be removed if the fundamental reason for them remains, namely, the presence of radionuclides in SNF. Hence, the solution to this problem can be found only through the application of nuclear-physical principles, methods, and means.

The problem is especially acute for such countries as Belgium, Great Britain, Germany, France, Switzerland, the Republic of Korea, and Japan, where the NPP power repletion ranges from 60 to 200 kW km^{-2}, while the size of the conditional parameter of 'radioactivity concentration' [2], which should be introduced by analogy with the power repletion parameter, exceeds the average value for countries using NPP power (1000 Ci km^{-2}) by a factor of 10 to 25.

2. An approach to the problem solution

Bearing in mind that there is no alternative to nuclear power engineering, the above problems would be solved in a radical manner, i.e., the nuclear power cycle must be restructured, with stages (B) – (D) replaced by an economically viable nuclear-physical procedure which would make it possible to transform (transmute) the most radiotoxic fission products into stable isotopes, to destroy transuranium actinides through the fission of their nuclei, and to return the regenerated uranium to the cycle in the form of new fuel. Here stage (A) must be augmented by the fractionation of the HRW after types of nuclides and with the recycling of the transmuted nuclides in order to extract stable isotopes — the transmutation products.

[2] Radioactivity concentration is a conditional parameter defined as the ratio of the SNF activity of national NPPs to the country's area.

Contemporary transmutation approaches, such as the electronuclear method [5] and the use of molten salt debris reactors [6], do not guarantee an ecologically full-fledged physical result, since by allowing the destruction of the actinide fractions of HRW such approaches cannot be applied to transmutation of most fission products and, primarily, ^{90}Sr and ^{137}Cs nuclides, whose neutron absorption cross sections are close to zero. Moreover, in the electronuclear method, where neutrons are produced through disintegration of the nuclei of the heavy target (Pb or Bi) by high-energy protons (~ 1 GeV), 'secondary' fission radionuclides are produced in a target [7], and among these radionuclides ^{210}Pb and ^{209}Po exceed any other nuclide in SNF in radiotoxicity and yield.

The use of the technologies associated with these approaches would be counterproductive because

- as the radiotoxicity with respect to air decreases, the equilibrium activity and radiotoxicity with respect to water increase because of the accumulation of fission fragments in addition to those supplied by the NPP, and in the case of the electronuclear method there is also an increase due to secondary radionuclide build-up;
- due to the impossibility of transmuting the fission fragments and the need to increase the volumes of the processing, storage, and burial of these fragments, all functions of the fuel-cycle back end remain unchanged, which excludes the possibility of structural economy and unquestionably leads to an increase in the cost of the nuclear fuel cycle.

Thus, these approaches do not provide a solution to the problem, since they keep the nuclear power cycle open. In addition to this, they provide no mechanism that would save the expenses of transmutation and hence are unfounded economically. The latter feature is not compensated for even partially by the possibility of increasing the plutonium credit, since the concentration of minority actinides in SNF is low compared to that of plutonium, and in conditions of critical breeding the conversion of nuclear fuel does not prevail over burn-up even in fast reactors, while in the electronuclear method the intensity of the proton beams is too low.

A consistent solution to the problem can be found by using the gamma – neutron transmutation method [8 – 10].

3. The gamma – neutron transmutation method: the essence and expected effects

The gamma – neutron transmutation method is based on the interaction between electrons that have been accelerated to a high energy and travel along a closed orbit in a specially designed electron storage ring and a spatially periodic pump field generated by devices placed in many straight sections of the orbit. Depending on the method's variant, the pump field may be a constant spatially periodic magnetic field or a pulsed field of the counterpropagating electromagnetic (laser) wave.

The directional gamma radiation generated as a result of multiple passage of the beam of ultrarelativistic electrons through the above-mentioned pump fields guarantees that there are photonuclear reactions in the many axisymmetric targets consisting of transmuted nuclides that are located on the beams of generated gamma radiation extracted from the accelerator, while the photoneutrons that are created in these reactions initiate the fission of the transuranium actinides loaded into the central part of the blankets surrounding the

targets. The fission neutrons are slowed down and are used for the transmutation of nonfissionable ^{238}U nuclei into fissionable nuclei in the spent uranium, which is loaded into the peripheral zone of the blankets after regeneration [10].

As a result of all this, there are three productive channels: a transmutation and neutron-producing γ-channel and two neutron channels, one of which is a transmutation channel, and the other a breeding channel. This makes it possible

(a) to transmute any fission products, primarily ^{90}Sr and ^{137}Cs nuclides, into stable isotopes and, at the same time, to produce high-intensity neutron fluxes;

(b) to destroy transuranium actinides by fissioning their nuclei and, at the same time, to multiply the neutrons produced in process (a);

(c) to utilize power-generating plutonium in process (b), and

(d) to convert fissile nuclides directly into regenerated uranium, ensuring a breading ratio (BR) close to unity and concentration of fissile nuclei needed for U – Pu fuel.

Below we will see that the above processes may be realized with a technologically acceptable productivity commensurate to the rate of fuel burn-up in modern reactors, without producing any 'secondary' radionuclides. Here, the energy inputs needed for transmutation and conversion may be balanced by the energy of fission of the transuranium actinides.

In such an approach, chemical regeneration of spent uranium is augmented by neutron regeneration of the uranium's power-generating potential, all products of the radiochemical processing of SNF are utilized as raw materials debited by the preceding fuel cycle and are used to produce fuel as credit for the next cycle, and the fuel is reprocessed without enrichment in ^{235}U or handling Pu in an open form, while only stable isotopes and low-activity radionuclides reach the environment.

In contrast to the methods mentioned earlier, the present method is also expedient because, thanks to the transmutation of ^{90}Sr and ^{137}Cs nuclides and destruction of transuranium actinides, the energy released by the products of stage (A) that must be immobilized and buried decreases dramatically, with the result that the volume of the buried materials also sharply decreases. The economy that emerges as a result at the back end of the fuel cycle is augmented by a reduction in the cost of the reproduced fuel and the corresponding "structural economy" at the front end of the cycle. Under certain conditions, the sum of these factors becomes large enough to fully compensate for the expenses on transmutation of the radioactive nuclides and the breeding of fissile nuclides.

Thus, the ecological adequacy of the gamma – neutron transmutation method makes it economically feasible, which resolves the contradiction inherent in the above approaches. Since the processing of SNF becomes profitable, the volumes of direct burial can be reduced and the number of recycles of natural uranium as fuel for NPPs increases severalfold.

4. The main processes and scheme of the electrophotonuclear cycle

The following processes must be implemented if we want the gamma – neutron transmutation method to work:

(1) electrons are accelerated to high (ultrarelativistic) energies, then built-up in storage rings, and finally collected into a beam in the form of bunches over the course of a long

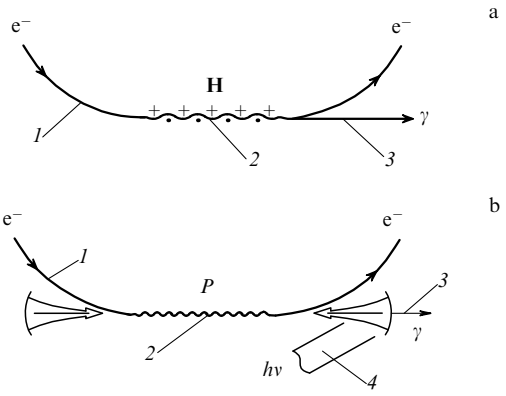

Figure 2. Elements of the gamma – neutron transmutation method: *1*, an element of the closed orbit of electrons accelerated to an energy *E*; *2*, one of the *n* straight sections of the orbit with a pump field produced by a constant spatially periodic magnetic field of strength *H* (a) and a field of a laser wave oscillating in the form of a pulse in an optical cavity with end mirrors focusing the pulsed power flux to a value *P* on the length of the interaction with electrons (b); *3*, a beam of magnetic bremsstrahlung (synchrotron radiation) in case (a) and gamma bremsstrahlung (undulator radiation) in the laser field in case (b), and *4*, a pulse of laser light from an external IR laser fed to the cavity.

period of time in their travel along a closed orbit in a specially designed electron storage ring accelerator;

(2) the energy of the accelerated electrons is transformed into that of the directional beams of gamma quanta via multiple passage of the bunches through the devices located along the straight sections of the orbit, devices with a spatially periodic pump field, which is a constant magnetic field (Fig. 2a) or an oscillating pulse of an electromagnetic (laser) wave (Fig. 2b);

(3) fission products are transmuted via photonuclear reactions in the numerous axisymmetric targets consisting of transmutable nuclides, reactions that are triggered by the beams of generated gamma radiation extracted from the accelerator;

(4) there is fission of the transuranium actinides located in the central part of the blankets surrounding the targets, a process induced by the gamma quanta scattered from a target and by photoneutrons and proceeding, as in a subcritical booster, with neutron multiplication with $K_{\text{eff}} < 1$, and

(5) there is moderation of fast neutrons in a heavy moderator, e.g., lead, to resonance energies, and transmutation of nonfissionable ^{238}U nuclei into fissionable nuclei in the spent uranium, which is located in the peripheral zone of the blankets after radiochemical regeneration.

The schematic of a target – blanket system is given in Fig. 3.

It is advisable to call a power cycle in which the main power-generating reaction of nuclei fission is augmented by the above processes an electrophotonuclear cycle. Such a cycle debits (a) energy as the result of nuclei fission by thermal neutrons in the reactor core and of transuranium nuclide fission by fast neutrons in the subcritical boosters of a transmutator – breeder; (b) fission and transuranium nuclides appearing as the fission reaction products; (c) neutrons as the result of irradiation of (b) products by high-energy photons, and (d) stable isotopes appearing as the products of gamma and neutron transmutation of fission fragments. Only the (a) and (d) products reach the environ-

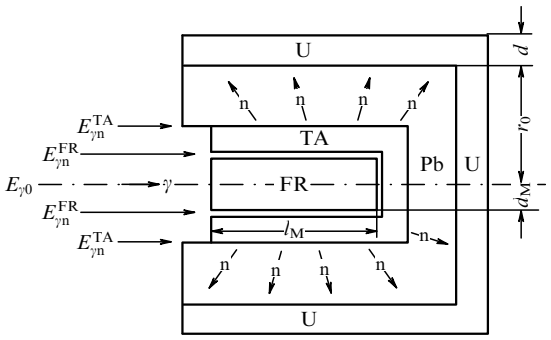

Figure 3. A target – blanket system of cylindrical geometry. The nuclides are arranged in the following pattern: fission radionuclides (FR) are located in the target, transuranium actinides (TA) are located in the central zone of the blanket, and regenerated uranium is located in the lead moderator on the peripheral zone of the blanket. Also shown is the space – energy distribution of the gamma quanta incident on the frontal surface of the system when undulator gamma radiation is generated in the field of a laser wave whose end-point energy in the spectrum was $E_{\gamma 0} = 30$ MeV.

ment, while the (b) radionuclides and uranium circulate in the cycle and do not leave it.

Such a cycle can be compared to the cycle of oxygen reproduction in nature (Fig. 4). Such comparison makes sense if U is taken to be the soil capable of reproducing the power-generating potential, the (b) products of the fission process to be the fruits, and the neutrons to be the seeds that are extracted from the fruits by a flux of photons and, landing in depleted soil (spent uranium), restore its power-generating potential by reproducing the power-generating objects (fissile nuclei). Since the binding energy of the nucleons in a nucleus exceeds the energy of a chemical bond by seven orders of magnitude, photon fluxes with an energy of approximately 15 MeV must be generated, so that the electrophotonuclear power cycle can proceed. The yield of the products in processes comprising the electrophotonuclear cycle is normalized to 100 disintegrating nuclei, of which roughly 35 nuclei, as follows from the isotopic analysis of SNF unloaded from a VVR-1000 reactor after a standard power production of 400 MW day $(\text{kg U})^{-1}$, are those of plutonium isotopes that form in ^{238}U blocks in the course of the reactor's operation. Hence, only 65% of the disintegrated nuclei must undergo conversion, which can be achieved, as we will see shortly, by using as sources of neutrons only ^{90}Sr, ^{135}Cs, ^{137}Cs, and ^{129}I nuclides, which amount only to 12% of the number of disintegrated nuclei.

Radiochemical support of the cycle under consideration should include:

(1) element-by-element extraction from spent uranium of nuclide fractions of fission products that must undergo transmutation and the fraction of transuranium actinides, including plutonium;

(2) transformation of the extracted nuclides into chemical compounds that suit to the conditions of gamma and neutron transmutation;

(3) transformation of the regenerated uranium into a chemical compound and the shape of fuel elements that agree with the conditions of subsequent use as U – Pu fuel, and finally

(4) recycling extraction and fractionation of the products of fission of transuranium actinides and the products of transmutation of fission fragments that comprise stable isotopes.

The structure of the electrophotonuclear power cycle is shown in Fig. 5. It differs dramatically from the one used in modern reactors in that the extracted nuclides, which belong to HRW, and the recovered uranium are utilized as raw materials: the former as a raw material generating neutrons and transformed in the process into stable isotopes, and the latter as a raw material absorbing the produced neutrons and

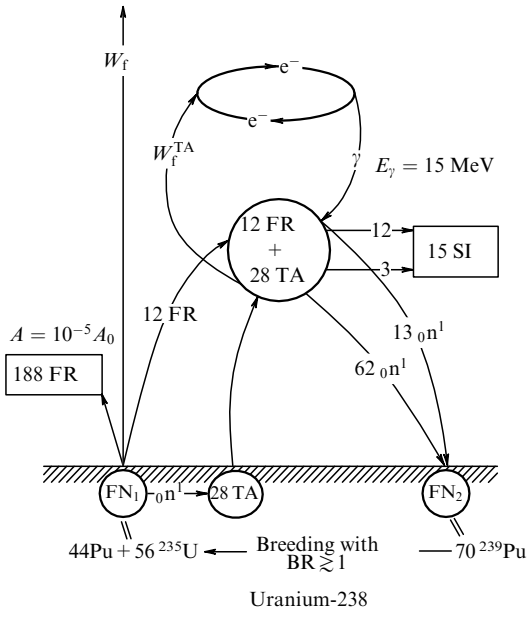

Figure 4. Functional diagram of the electrophotonuclear power cycle. The product yield at different stages of the cycle is normalized to 100 disintegrating nuclei. The following system of notation has been adopted: FN_1, the nuclei disintegrating in the first campaign period of the reactor in the NPP unit; TA and FR, the transuranium actinides and the fission radionuclides, respectively, that form in the cycle; SI, stable isotopes; FN_2, ^{239}Pu nuclei produced in the spent uranium as 'fuel' nuclei replacing the fissile ^{235}U nuclei belonging to the FN_1 category; W_f, the fission energy of the nuclei in the reactor, and W_f^{TA}, the fission energy of the nuclei of transuranium actinides in the blankets (the nuclei enclosed in rectilinear frames reach the environment).

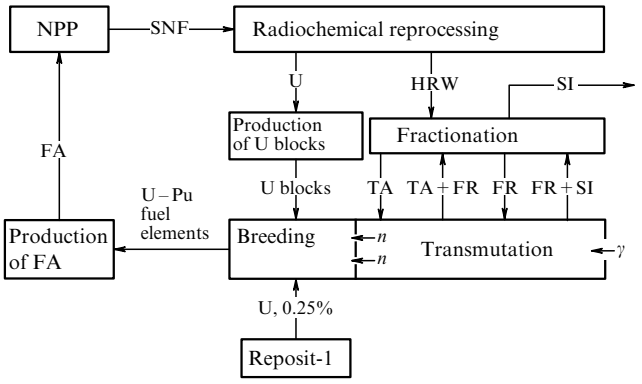

Figure 5. Structure of the electrophotonuclear power cycle. The fractionation of HRW extracted from SNF includes the transformation of the nuclide fractions that will undergo transmutation into the respective chemical forms and, if necessary, the separation of the isotopes of the fission fractions. The diagram does not show the transformation of the fission energy of actinide nuclei into electric energy to compensate for the expenditure of energy.

transformed in the process into a new fissile fuel. The nuclides that cannot be used in pure form are transformed into oxides or other compounds with low-Z elements possessing a neutron absorption cross section close to zero, while the regenerated uranium is transformed into a chemical compound and shaped as blocks whose size, material of the sheath, and other parameters agree with the technical specifications for U – Pu fuel elements. Here, the mass of the ^{235}U isotope burnt up in the previous fuel cycle of the NPP is balanced by adding natural or depleted uranium.

The fission products intended for transmutation and extracted from SNF of a single NPP unit are distributed among m axisymmetric targets placed in the peripheral zone of the orbit of the electron storage ring, the orbit having $n = km$ straight sections, where $k \gg 1$ is the number of NPP units operating in a cycle with a single storage ring. Each target is positioned on the extension of the axis of the straight section at a distance L_M from its center and is surrounded by a blanket of cylindrical geometry, into whose central part adjoining a target transuranium actinides are loaded, while uranium blocks are loaded into the peripheral part. The U blocks are placed in a lead moderator in the form of a layer of thickness d at a distance r_0 from the blanket axis (see Fig. 3). The actinides extracted from the SNF of a single NPP unit and the spent uranium of the unit that has been regenerated for further use as the fuel in the unit are distributed among m blankets. The structure and size of the blanket zones are selected in such a way that the fast neutrons produced in a target multiply in the central zone of the blankets as in a subcritical booster and their intensity is the same in all blankets and sufficiently high to achieve BR $\simeq 1$, with the probability of avoiding resonant absorption in the uranium blocks being minimal.

The energy of the electrons accelerated in the storage ring is chosen such that for a given strength and structure of the pump field the average energy for the spectrum of the generated gamma quanta lies near the maximum of the giant dipole resonance in the photonuclear cross section of the radionuclides located in the targets, and the electron current is chosen such that the transmutation of fragments, the destruction of transuranium actinides, and the conversion of fissile nuclei in uranium happen within a time interval equal to the campaign period of the reactors of the serviced NPP.

The transmutation of the fission radionuclides into stable isotopes takes place in the targets as a result of photonuclear reactions (γ, n), (γ, 2n), and (γ, p) directly or through the beta decay of short-lived daughter nuclei. The resulting photoneutrons and gamma quanta, scattered from the targets into the blankets, are used to initiate the fission of actinides and the multiplication of fast neutrons, which increases their intensity compared to that of the photoneutrons and gamma quanta generated in a target by a factor of $1/(1 - K_{\text{eff}})$, where $K_{\text{eff}} < 1$ is the fast multiplication factor.

The fission neutrons are moderated and, thanks to resonance capture in uranium blocks, transmute nonfissionable ^{238}U nuclei into fissionable. At the same time, the rate of transmutation of fission radionuclides and destruction of transuranium actinides increases. The fission energy of the latter is transformed into electric energy and is used to compensate for the energy inputs — the radiative losses of the electron beam in the generation of gamma radiation.

The gamma and neutron transmutation of fission nuclides and the destruction of transuranium actinides are done before each component is burnt up by $\sim 15 - 20\%$, after which stable isotopes are extracted from the targets, and fission fragments from the blankets; the radionuclides that have not burnt up are recycled for further transmutation, the targets and blankets are 'uploaded' with products of radiochemical processing of SNF, while the targets are additionally loaded with fission fragments of the destructed actinides up to the initial nuclide composition of the targets and blankets.

The build-up of the fissile nuclei in the regenerated uranium is continued up to the rated concentration for the U – Pu fuel, after which the uranium blocks enriched with fissile nuclei are extracted from the blankets and brought into a new fuel cycle of the NPP as fuel, which has been produced without additional transformations, enrichment in ^{235}U, or the use of pure plutonium.

The following factors must be taken into account if the efficiency of transmutation processes is to be raised and the energy expended on them is to be reduced:

(1) The targets must be fabricated only from the nuclide fractions of the Sr and Cs isotopes and also from the fraction of iodine that includes the most radiotoxic long-lived fragment ^{129}I; it is advisable to transmute this fragment, in addition to ^{90}Sr and ^{137}Cs, to a stable isotopic form. It is also sound practice to use laser isotope separation in order to separate the isotopes ^{90}Sr, ^{137}Cs, and ^{129}I from the corresponding stable fragments ^{88}Sr, ^{133}Cs, and ^{127}I. This is especially true of the I and Cs isotopes, since ^{127}I and ^{133}Cs have substantial resonance neutron absorption cross sections.

(2) There is no sense in fractionating and transmuting the nuclide fractions of Zr, Pd, Sn, and rare-earth elements, since they contain long-lived radionuclides (^{93}Zr, ^{107}Pd, ^{126}Sn, etc.) whose activity is low, and the concentration in the fraction does not exceed 15% and is insufficient for their effective transmutation. These nuclides should be placed into the category of waste of medium activity and should be buried.

(3) The long-lived ^{99}Tc isotope can be separated and placed into the blanket's moderator, but only if its neutron transmutation does not lower the BR.

(4) The smallness of the cross sections of photonuclear processes is balanced by the fact that secondary gamma radiation is used at its maximum. This radiation is generated because of Compton scattering of primary gamma quanta incident on a target and the bremsstrahlung of the produced Compton electrons and electron – positron pairs. Taking all these factors into account, we conclude that

- the average energy of the incident gamma quanta is selected from the condition $\langle E_\gamma \rangle \geqslant 15$ MeV, so that the larger part of their spectrum lies above the threshold of the photonuclear reactions (γ, n) and (γ, p) of fission radionuclides and overlaps the entire region of the giant dipole resonance for these reactions and the average energy of the quanta scattered from a target into the blanket is above the photofission threshold for the nuclei of transuranium actinides;
- the target length l_M is selected by the condition $l_M \geqslant 3\lambda_\gamma$ (where λ_γ is the path length of gamma quanta with an energy $\langle E_\gamma \rangle$ in the target material) in order to intensify the factors that determine the build-up of secondary gamma quanta within an energy range above the photonuclear reaction threshold and to increase the possibility of using them for transmutation and photofission;
- the target size in the transverse direction is chosen larger than the transverse size of the beam of gamma quanta by $k\lambda_{\gamma s} \sin\theta_\gamma$, where θ_γ is the scattering angle of gamma quanta with an energy $\langle E_\gamma \rangle$, $\lambda_{\gamma s}$ is the path length of gamma quanta in

the target after scattering, and the coefficient $k < 1$ if the fraction of photofission of transuranium actinides in the blanket must be increased and $k \geqslant 3$ if secondary gamma quanta are to be used at their maximum for transmutation of nuclides in a target.

The values of $\langle E_\gamma \rangle$, l_M, and d_M depend on the type of spectrum and the geometry of the beam of primary gamma radiation, which are determined by the type of emitting structure. Their optimal values must be found for each specific case either through experiments or as a result of numerical simulation of the transfer of a beam of directed gamma radiation with a given type of spectrum in a heterogeneous medium of a given nuclide composition and geometry.

The breeding ratio (BR), which is defined as the ratio of the number of fissile nuclei accumulated per unit mass in the future-cycle fuel to the number of nuclei burnt up per unit mass of fuel in the previous cycle, can be raised to unity and the quality of the converted fuel can be improved provided that

- power-generating plutonium is utilized together with minor actinides in the blanket's boosters, which ensures both the required value of K_{eff} and a lower value of α for thermal neutrons in the converted fuel;
- in the event that the breeding ratio does not reach its value of unity, the surplus of neutrons in the blankets is increased by adding to the blanket's boosters an additional amount of fast fissionable material, say, natural or depleted uranium stored as uranium 'reject' at isotope-separation plants.

5. Methods of implementation and the characteristics of processes in the electrophotonuclear energy cycle

5.1 Generation of gamma radiation

The possibility of using the stored energy of beams of electrons accelerated to ultrarelativistic energies in storage rings to generate high-intensity fluxes of gamma radiation and neutrons was first demonstrated by the present author in 1978 already [11] and was later frequently discussed as a possible way of creating a new generation of neutron sources, in particular, sources of polarized neutrons, to be used in fundamental research [12–16].

The applicability of the proposal for a task-oriented transmutation of radionuclides is obvious, since the state of a nucleus can be changed either via the photonuclear reactions (γ, n), (γ, 2n), and (γ, p) or as a result of the capture of the photoneutrons produced in the reaction (n, γ), and in the case of transuranium nuclei this can also be done by using the photofission reactions (γ, f) and the fission reactions by neutrons (n, f). A technologically acceptable intensity of transmutation processes can be achieved thanks to the unique properties of the radiation emitted by ultrarelativistic electrons, such as (a) the characteristic type of spectrum with a well defined edge or an exponential drop in the high-energy region (depending on the type of radiation — undulator or synchrotron [17]) and with a relatively low energy of the gamma quanta in the main part of the spectrum; (b) the extremely small divergence of the radiation (on the order of m_0c^2/E, where m_0 and E are the electron rest mass and energy, respectively); (c) the high spatial and spectral radiation density (which is determined by the above properties of the radiation), and (d) the high integral intensity caused by the high energy (up to 100 GeV [17]) and the huge average electron current in modern storage rings (up to 2.5 A [18]). Owing to the dependence of the end-point energy of the spectrum of the gamma quanta on the electron energy E and the parameters of the pump field, they can always be selected in such a way that the spectrum of the gamma quanta overlaps the entire range of energies near the giant dipole resonance in the cross sections of photonuclear reactions — from the threshold values $E_{\gamma n} \simeq 5-6$ MeV for transuranium nuclides and $E_{\gamma n} \simeq 9-10$ MeV for medium-mass fission nuclides to 25–30 MeV.

The above-mentioned properties of the radiation emitted by ultrarelativistic electrons ensure a high spatial and spectral density of the radionuclide transmutation and the photoneutron generation. The spectral density of gamma transmutation with allowance for multiple processes of Compton scattering of gamma quanta in a target and the bremsstrahlung of Compton electrons and electron–positron pairs can be represented by the following expressions [9]

$$\dot{N}_{\gamma\,\mathrm{tr}}(E_\gamma) = \dot{N}_{\gamma 0}\,\frac{A}{A-1}\,\Theta_{\gamma\,\mathrm{tr}}(E_\gamma)\,\Phi_\gamma(E_\gamma)\,, \tag{5}$$

$$\Theta_{\gamma\,\mathrm{tr}}(E_\gamma) = \frac{\sum_{x=1}^{2}\sigma_{\gamma,x\mathrm{n}}(E_\gamma) + \sigma_{\gamma,\mathrm{p}}(E_\gamma)}{\sigma_\gamma(E_\gamma)}\,, \tag{6}$$

$$\Phi_\gamma(E_\gamma) = \Phi_{\gamma 0}(E_\gamma)\Big\{1 - \exp\big[-\Sigma_\gamma(E_\gamma)\,l\big]\Big\} + \sum_{i=1}^{3}\Phi_{\gamma i}(E_\gamma)\,B_{\gamma i}(E_\gamma, \Sigma_\gamma l)\,, \tag{7}$$

$$\Phi_{\gamma 0}(E_\gamma) = K_\gamma \eta_\gamma(E_\gamma)\,\frac{1}{E_\gamma}\,, \tag{8}$$

where $\dot{N}_{\gamma 0}$ is the integral intensity of the gamma quanta incident on a target; $\Theta_{\gamma\mathrm{tr}}(E_\gamma)$ is the spectral yield function of the transmutation products created by gamma quanta with an energy E_γ; $\sigma_\gamma(E_\gamma)$, $\sigma_{\gamma,x\mathrm{n}}(E_\gamma)$, and $\sigma_{\gamma,\mathrm{p}}(E_\gamma)$ are the total cross section of electromagnetic interactions and the cross sections of the reactions (γ, xn) and (γ, p), respectively; $\Sigma_\gamma(E_\gamma)$ is the macroscopic cross section of attenuation of the gamma quanta with an energy E_γ in a target; $\Phi_{\gamma 0}(E_\gamma)$ is the spectrum of incident gamma quanta normalized to unity; $\Phi_{\gamma i}(E_\gamma)$ and $B_{\gamma i}(E_\gamma, E'_\gamma, l)$ are the spectra of gamma quanta and the spectral build-up factors for the above-mentioned electromagnetic properties, respectively; $\eta_\gamma(E_\gamma)$ and K_γ are the dimensionless spectral function and the normalization factor dependent on the type of gamma radiation used, and l is the target length along the direction of the incident beam of gamma quanta, with $l \gg 1/\Sigma_\gamma(E_{\gamma n})$.

The spectral density of photoneutrons produced in gamma transmutations is determined by the same relationships, except for Eqn (6), which must be replaced by the following:

$$\Theta_{\gamma,x\mathrm{n}}(E_\gamma) = \frac{\sum_{x=1}^{2} v_x \sigma_{\gamma,x\mathrm{n}}(E_\gamma)}{\sigma_\gamma(E_\gamma)}\,, \tag{9}$$

where $\Theta_{\gamma,x\mathrm{n}}(E_\gamma)$ is the spectral function of the photoneutron yield; v_x is the multiplicity of photoneutron processes: $v_x = 1$ and $v_x = 2$ for the reactions (γ, n) and (γ, 2n), respectively, while in the case of photofission $v_x \simeq 3$, and the remaining notation is the same as in formula (6).

The expressions used in Refs [12, 13, 15] for determining the photoneutron spectrum and energies are true only for

light nuclei (e.g., Be) and only for gamma quanta with the energy below the first excited state of nuclei. For intermediate mass nuclei and, moreover, for fissile nuclei, in which the energy level density is high, the contribution of single-particle processes is low and the collective excitation of a nucleus is predominant in the event of absorption of gamma quanta, with the result that the neutron spectrum becomes 'evaporative', which by its type and neutron energies is close to a fission spectrum.

The present author used the spectral build-up factors to analytically derive an expression only for Compton scattering and only in the first-order approximation. This expression is not given here because it does not fully solve the problem, while its derivation and answer would take up a lot of space. However, even partially accounting for multiple electromagnetic processes significantly alters the picture of relaxation of a flux of gamma quanta along the target length. An exact computation of the spectral build-up factors is possible only with the help of such a program as MCNP and is meaningful only if the method is implemented with the selected variant of radiating structures, nuclear composition, and target geometry.

The modern level of development of methods focused on accelerating and storing relativistic electrons, the generation of magnetic fields, and laser technology makes it possible to select the methods for generating directional beams of gamma quanta that are most suitable for the posed problem. One of these constitutes the traditional method of generating magnetic bremsstrahlung (synchrotron radiation) by sending bunches of ultrarelativistic electrons many times through devices with a constant spatially periodic magnetic field (wigglers), devices located in the straight sections of the storage ring's orbit. In this case, the integral radiation intensity $\dot{N}_{\gamma 0}$ in formula (5) is given by

$$\dot{N}_{\gamma 0} = N_{\gamma 1}\dot{N}_{\mathrm{e}}\,, \qquad N_{\gamma 1} = 6.24\times 10^{-2} H_0 \lambda_0 N_0\,, \tag{10}$$

where $N_{\gamma 1}$ is the intensity of the radiation emitted by an electron in its single passage through the wiggler; $\dot{N}_{\mathrm{e}}$ is the number of electrons passing through the wiggler in one second (the current in the storage ring), while H_0, λ_0, and N_0 are the amplitude of the magnetic field (in teslas), the length of one period (cm), and the number of wiggler periods.

The spectrum of the incident gamma quanta in expression (8) is determined by the dimensionless spectral function $\eta_\gamma(E_\gamma/E_{\mathrm{c}})$ of synchrotron radiation, depending on the parameter E_{c}, the so-called critical energy, above which a rapid exponential decrease in the radiation intensity begins; this parameter is given by the formula (see Refs [17, 19])

$$E_{\mathrm{c}} = 6.65\times 10^{-4} E^2 H_0\,, \tag{11}$$

where E_{c} is measured in megaelectron-volts, and the electron energy E in gigaelectron-volts.

For transmuted fission products, the peak of the dipole resonance in the cross section of photonuclear reactions is near 15 MeV [20]. If we assume that the value of E_{c} must also lie in this range, the energy E of the electrons in the storage ring must be selected equal to roughly 80 GeV, and $H_0 \sim 3.5$ T. In this case, the transmutation intensity is at its maximum, since at $\lambda_0 \simeq 20$ cm and $N_0 \simeq 25$, which are typical values for wigglers, each electron will emit $N_{\gamma 1} \sim 100$ quanta. The length of the orbit of such a storage ring may be as large as 12–15 km, so that a large number of radiation-emitting structures can be located along such an orbit, as well as high-frequency cavities to compensate for the radiative losses of the electron beam. The productivity of such an accelerator–transmutator will be limited only by the power of the high-frequency system and the removal of heat generated by the radiation from the vacuum chamber and targets, while the lifetime of the electron beam, which usually amounts to several hours, will be limited by the quantum fluctuations of the electron energy. The discussion of the latter problem goes beyond the scope of the present article, but some of the aspects of its solution can be found in Ref. [10].

Despite the fact that modern technologies make possible without question the building of such an electron storage facility with the above-mentioned parameters, it is desirable to find a variant of an accelerator with an electron energy that is ten times lower and, hence, one that is smaller. This is possible if for the radiation-emitting structure we use a counterpropagating laser wave of the IR range and, respectively, the undulator radiation mode [10, 16].

The number $N_{\gamma 1}$ of quanta emitted by an electron in a single passage in the field of the laser wave amounts to [16]

$$N_{\gamma 1} = \frac{4\pi}{3}\,\frac{\alpha N_0}{1-\cos\Theta}\,\frac{K^2}{K^2+1}\,, \tag{12}$$

$$K = \frac{25.6}{c}\,(1-\cos\Theta)\,\lambda_0\sqrt{P}\,, \tag{13}$$

where $\alpha = 1/137$ is the fine-structure constant, N_0 is the number of field oscillations along the length of interaction of the laser and electron beams, Θ is the angle between the directions of propagation of the IR radiation and the electron beam, λ_0 is the emission wavelength (μm), and P is the radiation power flux density (W cm^{-2}) in the interaction region.

The end-point energy of the spectrum of the gamma quanta emitted in the field of the laser wave is given by

$$E_{\gamma 0} = 2\gamma^2 E_0 (1-\cos\Theta)\,, \tag{14}$$

where $\gamma = E/m_0c^2$, and $E_0 = 1.24/\lambda_0$ is the energy (in electron-volts) of the IR radiation quantum.

The average energy of the gamma quanta equals $E_{\gamma 0}/2$. In the case of IR radiation, to achieve the average energy of the spectrum near 15 MeV with, according to (12) and (13), the most appropriate maximum possible wavelength $\lambda_0 = 10.6$ μm (the light from a carbon-dioxide laser), one should use a beam of electrons accelerated to an energy $E \sim 4$ GeV.

Formulas (12) and (13) suggest that when electrons interact with continuous laser light, the radiation intensity is very low even in the case of hypothetical employment of a carbon-dioxide laser with the highest possible output power of 1 MW.

In Refs [10, 16], the use of a pulsed carbon-dioxide laser was suggested in order to increase the radiation intensity, while the emitting structure was to be a passive optical cavity with end focusing mirrors located on the axis of a straight section of the electron orbit, outside its range and at equal distances from its center, being spaced $L_{\mathrm{r}} = C_0/2n_0$ apart, where C_0 is the orbit's length, and $n_0 \gg 1$ is the number of bunches in the electron beam traveling along the orbit. The laser beam must be focused in such a way that its transverse

size is not smaller than the size of the electron beam, while the pump field power density must be at its maximum within the length $L_0 \leqslant L_s$ of the beam interaction along the cavity's axis, where L_s is the length of the straight section. A single laser pulse of length $\tau_l = 2L_0/c$ is fed to the cavity and is directed along its optical axis at an angle Θ to the direction of the electron counter motion, with the phase selected in such a way that the laser pulse meets each electron bunch at the beginning of a straight section. The generated gamma radiation is extracted through the frontal mirror of the cavity, having in mind the smallness of the cross sections of the electromagnetic processes in the region of the giant resonance of photonuclear reactions and minimizing the losses in intensity by reducing the thickness of the mirror on the axis of the gamma beam within its cross-sectional area (Fig. 2b).

A laser pulse in such a laser-optical system oscillates in the end cavity as a wave packet synchronously and in antiphase with the electron bunches traveling through the cavity, and the phasing is fulfilled in such a way that the pump field strength reaches its maximum in the interaction region each time an electron bunch passes through that region. Then it is only logical to call the radiating structure a laser undulator, and the generated radiation a bremsstrahlung in the field of a laser wave [16]. When the off-duty ratio $\nu\tau_r \sim 1$, with ν being the repetition frequency of the carbon-dioxide laser pulses, and τ_r the lifetime of such pulses in the cavity, the laser undulator may be compared in generation effectiveness to the magnetic undulator.

The optimal geometry is the one with $\Theta = \pi$. In this case, the length of the region in which the laser and electron beams interact and the value of the end-point energy $E_{\gamma 0}$ are at their maxima. The energy of the emitted gamma quanta depends on the angle at which they are emitted with respect to the axis of the straight section of the electron orbit, with gamma quanta of the energy $E_{\gamma 0}$ being emitted at a zero angle along the beam axis in the direction of electron beam propagation. For circularly polarized laser radiation, we have the optimal (cylindrical) geometry of the beam of emitted gamma quanta and, respectively, of the irradiated target. In this case, it is advisable to select the distance to the target, L_M, such that the energy of the gamma quanta incident on the frontal surface of the target – blanket system along the target – blanket interface is equal to the threshold energy of the reaction (γ, n) involving the nuclei of the fission radionuclides (see Fig. 3). This makes it possible to use the larger part of the spectrum of incident primary gamma quanta and all the secondary quanta that have been Compton-scattered from a target to the central part of the blanket with energies above the threshold energy of the reactions (γ, n) and (γ, f) involving transuranium actinides.

5.2 The products of gamma – neutron transmutation

Table 6 lists the data on the nuclides that determine the activity of the SNF unloaded from the NPP repository after 10 years of storage, the values of their equilibrium activity A_0, and the activity A_1 that accumulates linearly in the 42 years of operation of the unit. Compared to Table 1, Table 6 does not contain the data on nuclides with $T_{1/2} < 10$ years (for obvious reasons). All the nuclides listed are subject to transmutation, except for long-lived fission fragments whose contribution to the total activity does not exceed 10^{-5}.

The transmutation routes for ^{90}Sr, ^{129}I, and ^{137}Cs and the accompanying stable isotopes in the reactions (γ, n), (γ, 2n), (γ, p), and (n, γ) are shown in Fig. 6, and the transmutation products are listed in Table 7. Listed are the initial content of each isotope in the nuclide fraction and the relative efficiency of the transmutation channels, i.e., the product yield per transmutable nucleus for each gamma-transmutation channel and neutron channel, as well as the relative yield of the product fraction. The products assigned for recycling are labelled by a subscript 'r'. The efficiency of transmutation via the gamma channel is determined in the approximation of a single interaction between primary gamma quanta and the target, while the efficiency for the neutron channel is determined on the assumption that the flux of resonance neutrons in the target is lower than the flux of the gamma quanta by a factor of 100.

Table 6. Activity of nuclides in the unloaded SNF produced by an NPP 1-GW (el.) unit.

Nuclide*	A_0, MCi	Nuclide**	A_1, MCi
^{90}Sr	215	^{237}Np	0.001
^{137}Cs	306	^{238}Pu	3.5
^{241}Pu	98.5	^{239}Pu + ^{240}Pu + ^{242}Pu	1.1
^{243}Cm + ^{244}Cm	1.9	^{241}Am + ^{243}Am	0.2
		Fission fragments	0.008
Total	621.4	Total	4.81

* Nuclides with 10 years $\leqslant T_{1/2} \leqslant$ 30 years.

** Nuclides with $T_{1/2} \gg$ 30 years.

The data on transuranium actinides are not given, since only the fission of these actinides by gamma quanta and neutrons is important, the transmutation products of this fusion not differing from those listed in Table 7, while the other reactions lead only to the formation of neighboring transuranium isotopes and their subsequent fission (Fig. 7). The data presented in Table 6 suggest that the transmutation of the medium-lived fission fragments ^{90}Sr and ^{137}Cs, the destruction of transuranium actinides through fission of their nuclei and the subsequent transmutation of the fission fragments being formed — all these factors lower the activity of NPP wastes that are stored and buried by a factor of 10^5. Table 7 shows that no secondary radionuclides form in the process.

5.3 Photoneutronics of gamma – neutron transmutation

Tables 8 and 9 give the partial and total yields of the gamma and neutron channels per incident gamma quantum: in Table 8 for a model fission radionuclide (FR), and in Table 9 for a model transuranium actinide (TA). Since the photonuclear cross sections for ^{90}Sr have yet to be measured, the calculations were done for ^{88}Sr, since among the transmutable fission products it has the highest reaction threshold $E_{\gamma n} \simeq 10$ MeV and the smallest photonuclear cross sections. From the actinides we selected ^{137}Np, whose values of the reaction threshold and cross sections of photonuclear reactions are typical of transuranium isotopes. The photonuclear cross sections have been averaged over the spectrum of incident gamma quanta, as well as the cross sections of competing electromagnetic processes, which for Sr and Np atoms are assumed equal to 5.0 and 20 b, respectively. The estimates were made for gamma radiation generated in the field of a laser wave. The end-point energy of the gamma-quanta spectrum, $E_{\gamma 0}$, is about 30 MeV, which corresponds to the average energy $\langle E_\gamma \rangle \simeq 15$ MeV. We have allowed only for single interactions between the primary gamma quanta and a target. The photonuclear cross sections were taken from data

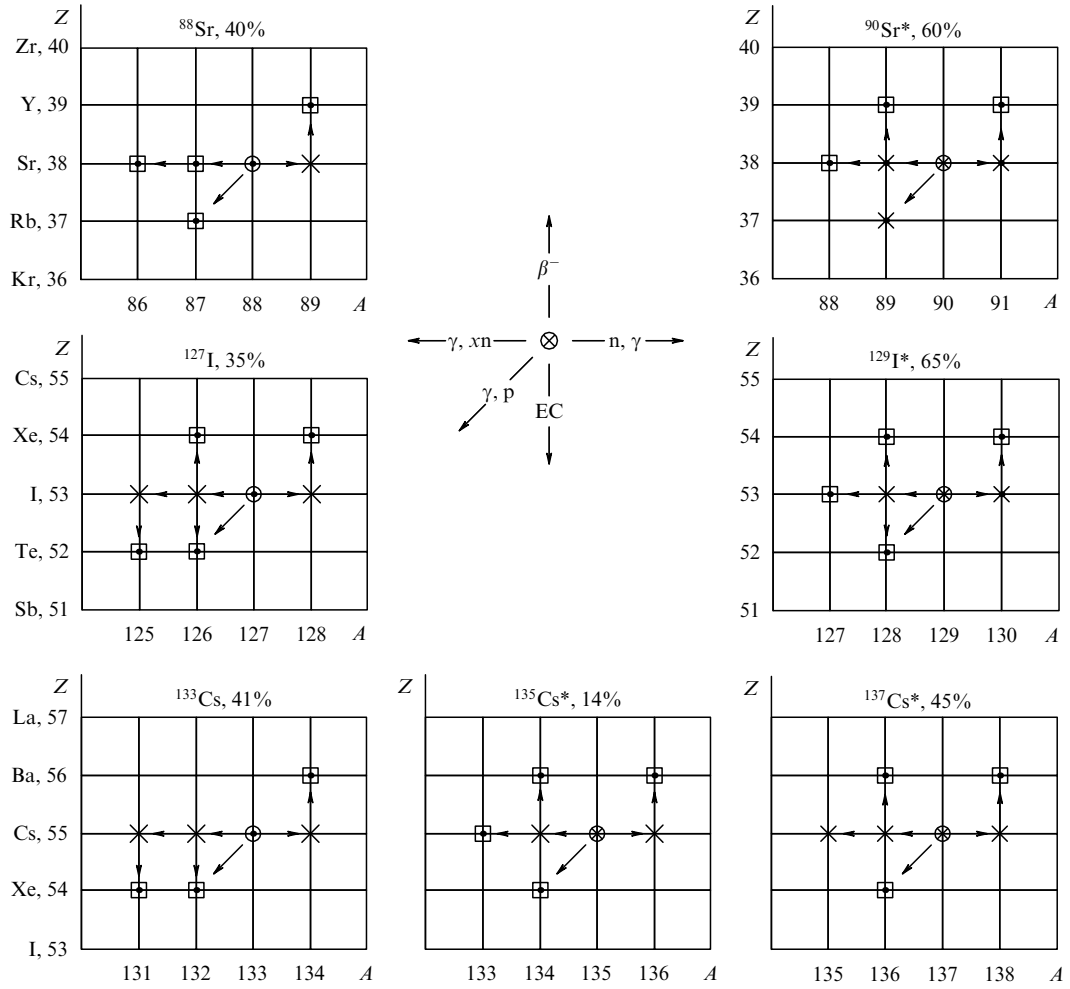

Figure 6. The routes of gamma and neutron transmutation of ^{90}Sr, ^{137}Cs, ^{135}Cs, and ^{129}I nuclides and the accompanying stable isotopes that are fractionated together with them in the regeneration of spent uranium. For each isotope we give its relative content in the nuclide fraction in the SNF of a VVR-1000 reactor. The following notation was used: ⊗, transmutable radionuclide; ⊙, the accompanying stable isotope of the fraction; ×, short-lived beta-active daughter isotope, and ⊡, product stable isotope. The transmutation nuclear reactions are depicted in the center of the figure.

Table 7. Products of gamma – neutron transmutation of the Sr, I, and Cs fractions.

Raw material	Gamma-channel products	Neutron-channel products	Fraction products
^{88}Sr, 0.40 ^{90}Sr*, 0.60	^{87}Rb, 0.06; ^{86}Sr, 0.02; ^{87}Sr, 0.19 ^{88}Sr$_r$, 0.03; ^{89}Y, 0.37	^{89}Y, 0.13 ^{91}Zr, 0.20	Rb, 0.06; Sr$_r$, 0.24 Y, 0.50; Zr, 0.20
^{127}I, 0.35 ^{129}I*, 0.65	^{125}Te + ^{126}Te, 0.01; ^{126}Xe, 0.02 ^{128}Te, 0.04; ^{127}I, 0.01; ^{128}Xe, 0.12	^{128}Xe, 0.32 ^{130}Xe, 0.48	Te, 0.05; I, 0.01 Xe, 0.94
^{133}Cs, 0.41 ^{135}Cs*, 0.14 ^{137}Cs*, 0.45	^{131}Xe + ^{132}Xe, 0.02; ^{134}Xe, 0.01; ^{133}Cs < 0.01; ^{134}Ba, 0.02 ^{136}Xe, 0.10; ^{135}Cs*, 0.04; ^{136}Ba, 0.32	^{134}Ba, 0.40 ^{136}Ba, 0.12 ^{138}Ba, ~ 0	Xe, 0.13 Cs$_r^*$, 0.04 Ba, 0.86

compilation [20], and the cross sections of electromagnetic interactions from Ref. [21].

The transmutation product yield per incident quantum in the ith channel, ε_{tr}^i (the efficiency of the ith channel), can be found from formulas that follow from Eqns (5)–(7):

$$N_{tr}^i = N_\gamma^i \frac{\langle\sigma_{tr}^i\rangle}{\sigma_t^{em}}\left[1-\exp(-\Sigma_{em}l)\right] \simeq N_\gamma \varphi^i \frac{\langle\sigma_{tr}^i\rangle}{\sigma_t^{em}}\,, \qquad (15)$$

$$\varepsilon_{tr}^i = \frac{N_{tr}^i}{N_\gamma} = \varphi^i \frac{\langle\sigma_{tr}^i\rangle}{\sigma_t^{em}}\,, \qquad (16)$$

where N_{tr}^i is the number of transmutation acts in the ith channel, N_γ and N_γ^i are the total number of gamma quanta and the number of quanta incident on a target in the range of energies E_γ of the ith photonuclear reaction, $\langle\sigma_{tr}^i\rangle$ is the value of the cross section of the ith reaction for an FR or TA averaged over this energy range, σ_t^{em} and Σ_t^{em} are the total micro- and macroscopic cross sections of electromagnetic processes on the proper atoms (equal to the sum of cross sections of the Compton scattering of incident gamma quanta and the production of electron–positron pairs, averaged over the same range of gamma-quanta energies),

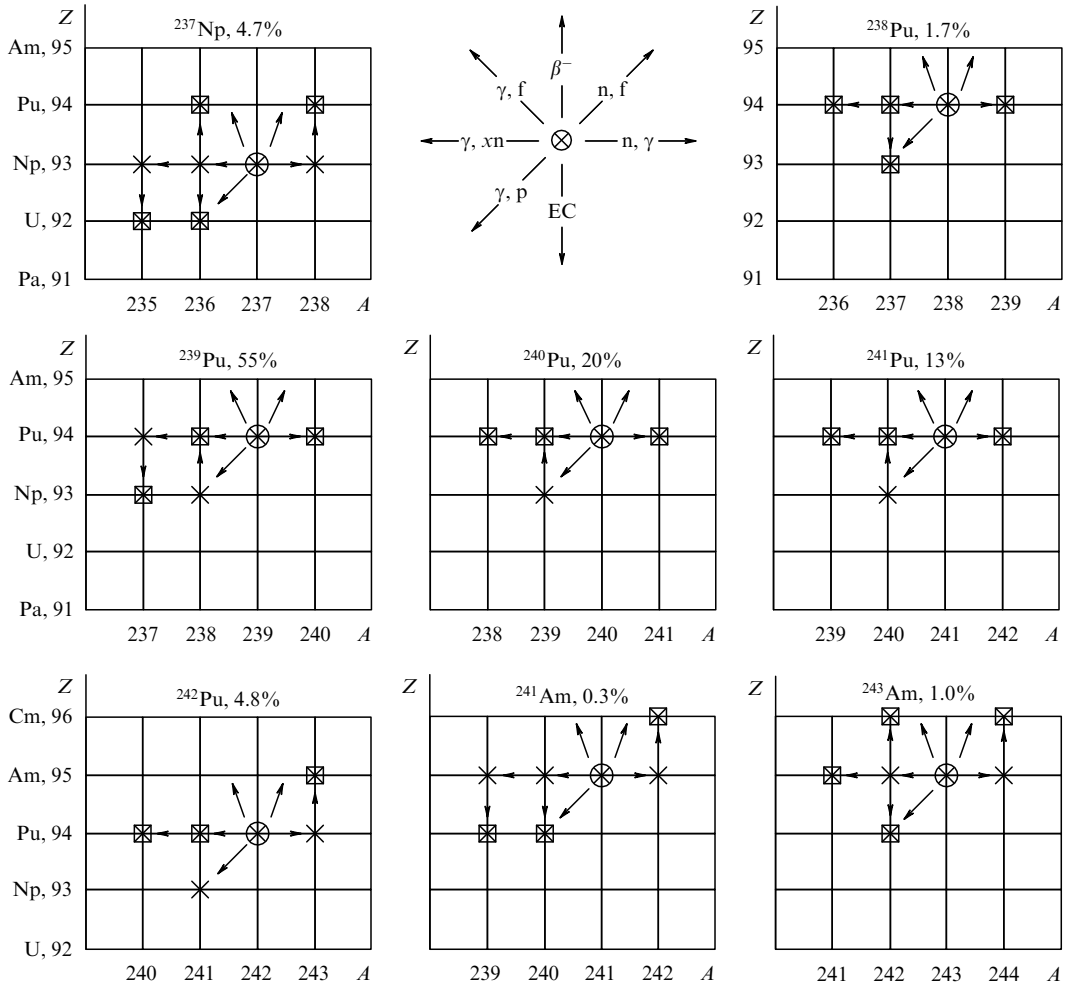

Figure 7. The routes of transmutation and destruction of the ^{237}Np and Pu and Am isotopes in the gamma and neutron channels. For each isotope we give its relative content in the total fraction of transuranium actinides in the SNF of a VVR-1000 reactor. The following notation was used: ⊗, transmutable radionuclide, and ⊠, long-lived daughter radionuclides undergoing fission as they accumulate in the blanket. For transuranium actinides, fission fragments are product nuclides. They are subject to fractionation, and the most radiotoxic are subject to recycling in the target and transmuting according to the schemes in Fig. 5.

Table 8. Efficiency of gamma-transmutation channels of a model FR.

Parameter	γ, n	γ, p	γ, 2n	Effective value
Reaction threshold $E_{\gamma i}$, MeV	10	10	18	—
Reaction cross section $\langle\sigma_{\gamma i}\rangle$, b	0.20	0.06	0.04	0.2
Fraction of quanta with E_γ from $E_{\gamma i}$ to $E_{\gamma 0}$	0.70	0.70	0.45	—
Channel efficiency $\varepsilon_{\mathrm{tr}i}$, acts (quantum)$^{-1}$	0.028	0.0085	0.0035	$\sum_i \varepsilon_{\mathrm{tr}i} = 0.040$
Neutron yield ν_i in reaction	1	—	2	1.1
Neutron yield $\varepsilon_{\mathrm{n}i}$ in channel, neutrons (quantum)$^{-1}$	0.028	—	0.007	$\sum_i \varepsilon_{\mathrm{n}i} = 0.035$

Table 9. Efficiency of gamma-transmutation channels of a model TA.

Parameter	γ, n	γ, f	γ, 2n	Effective value
Reaction threshold $E_{\gamma i}$, MeV	6.0	5.0	12	—
Reaction cross section $\langle\sigma_{\gamma i}\rangle$, b	0.20	0.30	0.10	0.2
Fraction of primary quanta with E_γ from $E_{\gamma i}$ to $E_{\mathrm{yn}}^{\mathrm{FR}}$	0.18	0.20	0	—
Fraction of secondary quanta with E_γ from $E_{\gamma i}$ to $E_{\gamma 0}$	0.26	0.27	0.20	—
Channel efficiency $\varepsilon_{\mathrm{tr}i}$, acts (quantum)$^{-1}$	0.0045	0.0070	0.0010	$\sum_i \varepsilon_{\mathrm{tr}i} = 0.0125$
Neutron yield ν_i in reaction	1	3	2	2.2
Neutron yield $\varepsilon_{\mathrm{n}i}$ in channel, neutrons (quantum)$^{-1}$	0.0045	0.021	0.002	$\sum_i \varepsilon_{\mathrm{n}i} = 0.0275$

and φ^i is the fraction of gamma quanta in the spectrum of undulator radiation normalized to unity (this fraction belongs to the range of energies of the ith photonuclear reaction).

The photoneutron yield per incident quantum in the ith channel, or the efficiency of neutron generation, is given by the formula

$$\varepsilon_{\rm n}^i = \nu_{\rm n}^i \varphi^i \frac{\langle \sigma_{\rm tr}^i \rangle}{\sigma_{\rm t}^{\rm em}}\,, \tag{17}$$

where $\nu_{\rm n}^i$ is the number of photoneutrons produced in the ith photonuclear reaction.

For the transuranium actinides placed in the central zone of the blanket, the spectral fraction of the gamma quanta that implement transmutation can be estimated as

$$\varphi^i = \varphi_{\rm B}^i + \varphi_{\rm TB}^i\,, \tag{18}$$

where $\varphi_{\rm B}^i$ is the fraction of the initial quanta incident on the frontal surface of the central zone in the range of energies E_γ from the threshold $E_{\gamma{\rm i}}^{\rm TA}$ of the ith reaction of a model TA to the threshold $E_{\gamma{\rm i}}^{\rm FR}$ of the same reaction on the nucleus of a model fission radionuclide, and $\varphi_{\rm TB}^i$ is the fraction of quanta that are Compton-scattered from target to blanket in an energy range from $E_{\gamma{\rm i}}^{\rm TA}$ to the end-point energy $E_{\gamma 0}$ of the spectrum of undulator radiation, equal to

$$\varphi_{\rm TB}^i = \varphi^i \frac{\sigma_{\rm Compt}}{\sigma_{\rm t}^{\rm em}}\,, \tag{19}$$

with $\sigma_{\rm Compt}$ and $\sigma_{\rm t}^{\rm em}$ being the cross section of Compton scattering and the total cross section of electromagnetic processes for an atom of a model FR.

The results are summarized in Table 10 and suggest that, within the adopted approximations and with complete utilization of the neutrons produced, the total yield of the products of transmutation along gamma and neutron channels amounts to about 0.1 nucleus per incident gamma quantum, and the energy 'cost' of a transmutation act is $E_{\gamma 1} \simeq 150$ MeV. With allowance for the efficiency $\eta_{\rm el-\gamma} \sim 0.75$ of modern storage rings, the cost will be $W_{\gamma 1}^{\rm el} = E_{\gamma 1}/\eta_{\rm el-\gamma} \simeq 200$ MeV (el.).

It must be noted that as the number of neutrons in the nucleus grows, the binding energy and, respectively, the threshold energy $E_{\gamma{\rm n}}$ of the reaction (γ, n) decrease, while the cross section increases. For instance, $E_{\gamma{\rm n}}$ for ^{90}Sr is 1.5 MeV lower than for ^{88}Sr, while the cross section may increase by 10%. The rate of the photonuclear reactions and the intensity of photoneutron production are proportional to the integral of the cross section over the gamma-quantum spectrum from $E_{\gamma{\rm n}}$ to $E_{\gamma 0}$. Hence, for ^{90}Sr, as well as for the other radionuclides considered here, one should expect a higher total yield compared to the estimates made here (approximately a 20% increase) and a similar decrease in the specific energy inputs.

Table 10. Efficiency of transmutation and generation of photoneutrons.

Nuclides	$\varepsilon_{\rm tr}$, acts (quantum)$^{-1}$	$\varepsilon_{\rm n}$, neutrons (quantum)$^{-1}$	$\varepsilon_{\rm tr} + \varepsilon_{\rm n}$
Fission	0.040	0.035	0.075
Transuranium	0.0125	0.0275	0.040
Total	0.0525	0.0625	0. 115

5.4 Compensation for transmutation energy expenditures

To fully compensate for the energy inputs, the blankets are loaded with additional fissionable material, e.g., natural or depleted uranium, which is arranged in the shape of a layer in the central zone of the blanket, adjoining the target and acting as a booster. The required number of ^{238}U nuclei can be found from the equation

$$P_{\rm E} = W_{\rm B} - W_{\rm T} = W_{\rm fl}^{\rm el}(N^{\rm TA} + N^8) - W_{\gamma 1}^{\rm el} N^{\rm FR} = 0\,, \tag{20}$$

where $P_{\rm E}$ is the energy surplus; $W_{\rm B}$ is the energy produced in the boosters by fission of the nuclei of transuranium nuclides and ^{238}U; $W_{\rm T}$ is the energy expended on generating the gamma radiation directed at the targets; $N^{\rm FR}$, $N^{\rm TA}$, and N^8 are the total number of FRs in m targets, the total number of nuclei of the transuranium actinides in m boosters, and the sought number of ^{238}U nuclei, respectively; $W_{\rm fl}^{\rm el} = E_{\rm fl}\eta_{\rm f-el}$, with $E_{\rm fl} \simeq 200$ MeV being the energy released in the fission of a ^{238}U nucleus or a transuranium nuclide, and $\eta_{\rm f-el} \simeq 0.3$ the efficiency of transformation of the thermal energy of nuclear fission into electric energy.

5.5 Photoneutronics of the breeding of fissile nuclei

Below we present the results of calculating the photoneutronics of the process of conversion of fissile nuclei in regenerated uranium for a target–blanket system whose nuclear composition is close to its optimum. The target contains separated isotopes ^{90}Sr, ^{129}I, and ^{135}Cs + ^{137}Cs, and to fully compensate for the energy expenditures an amount of ^{238}U is added to the total amount of transuranium actinides (^{237}Np and isotopes of Pu, Am, and Cm) in the central zone of the blanket in a proportion determined by equation (20).

The calculation is done for a realistic content of radionuclides in the fuel unloaded from a VVR-1000 reactor after the standard thermal production of 40 MW day (kg U)$^{-1}$ has been achieved. To determine the sensitivity limit, we used the data of the Dollezhal' R&D Institute of Power Engineering (NIKIET) [22] and the Russian Research Centre 'Kurchatov Institute' (RNTs KI) [23]. The algorithm of the calculation and the results are presented in Table 11.

The photonics calculation was done on the basis of the data listed in Tables 9 and 10 for model nuclides, since the photonuclear cross sections of ^{238}U nuclide are close to those of ^{237}Np. All neutron computations involve the use of the recommended multigroup constants [24], and the results are averaged over the fission neutron spectrum with allowance for real concentrations of nuclides in SNF.

The number of photoneutrons $N_{\gamma{\rm n}}^{\rm FR}$ that form in the targets as a result of gamma transmutation of FRs (item 2.1 in Table 11) is given by the formulas

$$N_{\gamma{\rm n}}^{\rm FR} = \langle \nu_{\gamma,x{\rm n}} \rangle N^{\rm FR}\,, \tag{21}$$

$$\langle \nu_{\gamma,x{\rm n}} \rangle = \frac{\varepsilon_{\rm n}^{\gamma,{\rm n}} + \varepsilon_{\rm n}^{\gamma,2{\rm n}}}{\varepsilon_{\rm tr}^{\gamma,{\rm n}} + \varepsilon_{\rm tr}^{\gamma,2{\rm n}}}\,, \tag{22}$$

where $\langle \nu_{\gamma,x{\rm n}} \rangle = 1.1$ is the photoneutron yield averaged over the (γ, n)- and (γ, 2n)-reaction channels, and the other quantities were defined in Eqns (16) and (17) and are given in Table 8.

The number of photoneutrons $N_{\gamma{\rm n}}^8$ produced in ^{238}U by the gamma quanta scattered from a target into the central zone (CZ) of the blanket and incident on the blanket's frontal surface in the energy range $5 \leqslant E_\gamma \leqslant 10$ MeV (item 2.2 in

Table 11. Photoneutronics of the conversion of fissile nuclei.

Parameters of the process of conversion of fissile nuclei per 1 kg U	Estimates according to the data of	
	NIKIET	RNTs KI
(1) Production of nuclei in fuel of VVR-1000		
1.1 $N_{\rm f}^5$ nuclei of ^{235}U fissioned	6.50×10^{22}	6.43×10^{22}
1.2 $N^{\rm FR}$ nuclei of ^{90}Sr, ^{129}I, ^{135}Cs and ^{137}Cs produced	1.20×10^{22}	1.40×10^{22}
1.3 $N^{\rm TA}$ nuclei of Np, Pu, Am and Cm produced	2.35×10^{22}	3.14×10^{22}
(2) Generation of photoneutrons in target and blanket		
2.1. $N_{\gamma n}^{\rm FR}$ photoneutrons produced in an FR target	1.34×10^{22}	1.55×10^{22}
2.2 $N_{\gamma n}^8$ photoneutrons form from ^{238}U in blanket CZ	1.05×10^{22}	1.22×10^{22}
2.3 Total of $N_{\gamma n}^{\Sigma} = N_{\gamma n}^{\rm FR} + N_{\gamma n}^8$ photoneutrons produced	2.39×10^{22}	2.77×10^{22}
2.4 Of these, $N_{\gamma n}^{\rm a}$ photoneutrons absorbed in ^{238}U and TA	3.86×10^{21}	4.47×10^{21}
2.5 Source-neutron surplus $N_{\gamma n}^{\rm TB} = N_{\gamma n}^{\Sigma} - N_{\gamma n}^{\rm a}$	2.00×10^{22}	2.32×10^{22}
(3) Source-neutron multiplication in blanket		
3.1 $N_{\gamma f}^8$ nuclei of ^{238}U fissioned by gamma quanta according to item 2.2	2.10×10^{21}	2.45×10^{21}
3.2 $N_{\rm nf}^{\rm TA+8}$ nuclei of TA and ^{238}U fissioned by neutrons according to item 2.4	2.79×10^{21}	3.24×10^{21}
3.3 Multiplication with $K_{\rm eff}$ required according to Eqn (21)	0.915	0.925
3.4 $N_{\rm fn}^{\rm B} = N_{\rm fn}^{\rm TA+8}$ neutrons produced in multiplication	4.18×10^{22}	5.66×10^{22}
3.5 Total of $N_{\rm n}^{\Sigma} = N_{\gamma n}^{\rm TB} + N_{\rm fn}^{\rm B}$ neutrons produced in the system	6.18×10^{22}	7.98×10^{22}
(4) Build-up of fissile nuclei in regenerated uranium		
4.1 Neutron utilization factor f in moderation	0.973	0.973
4.2 Resonance-neutron utilization factor $f_{\rm r}$	0.982	0.982
4.3 $N_{\rm br}^9 = \langle f \rangle N_{\rm n}^{\Sigma}$ fissile nuclei form in regenerated U	6.04×10^{22}	7.80×10^{22}
4.4 Attainable BR	0.93	1.21

Table 11) is given by the formulas

$$N_{\gamma n}^8 = \langle \nu_{\gamma,\,xn}^8 \rangle \, \frac{\varepsilon_{\rm tr}^8 N^{\rm FR}}{(\varepsilon_{\rm tr}^{\gamma,\,n} + \varepsilon_{\rm tr}^{\gamma,\,2n})^{\rm FR}} \,, \tag{23}$$

$$\langle \nu_{\gamma,\,xn}^8 \rangle = \frac{\varepsilon_{\rm n}^{\gamma,\,n} + \varepsilon_{\rm n}^{\gamma,\,2n} + \varepsilon_{\rm n}^{\gamma,\,f}}{\varepsilon_{\rm tr}^{\gamma,\,n} + \varepsilon_{\rm tr}^{\gamma,\,2n} + \varepsilon_{\rm tr}^{\gamma,\,f}} \,, \tag{24}$$

$$\varepsilon_{\rm tr}^8 = \sum_{i=1}^{3} \varepsilon_{\rm tr}^{8i} \,, \qquad \varepsilon_{\rm tr}^{8i} = \varphi^{8i} \, \frac{\langle \sigma_{\rm tr}^{8i} \rangle}{\sigma_{\rm t}^{8\rm em}} \,, \tag{25}$$

where $\langle \nu_{\gamma,\,xn}^8 \rangle = 2.2$ is the photoneutron yield from ^{238}U, averaged over the reactions (γ, n), (γ, 2n), and (γ, f); $\varepsilon_{\rm tr}^8$ is the efficiency of gamma transmutation of ^{238}U, averaged over the channels; φ^{8i} was defined in Eqns (18) and (19), and the other quantities were defined in Eqns (16) and (17).

The number of photoneutrons $N_{\gamma n}^{\rm a}$ absorbed in ^{238}U and transuranium actinides (item 2.4 in Table 11) is determined from the formula

$$N_{\gamma n}^{\rm a} = N_{\gamma n}^{\Sigma} \, \frac{\sigma_{\rm c}^{\rm TA+8} + \sigma_{\rm f}^{\rm TA+8}}{\sigma_{\rm t}^{\rm TA+8}} \,, \tag{26}$$

where $N_{\gamma n}^{\Sigma}$ is the total number of photoneutrons produced in a target and the central zone of the blanket, while $\sigma_{\rm c}^{\rm TA+8}$, $\sigma_{\rm f}^{\rm TA+8}$, and $\sigma_{\rm t}^{\rm TA+8}$ are the capture and fission cross sections and the total cross section for fast neutrons averaged over the spectrum and the nuclide concentrations, including the concentration of ^{238}U.

The number $N_{\gamma f}^8$ of ^{238}U nuclei fissioned by gamma quanta in the generation of neutrons in accordance with item 2.2 in Table 11 and taken into account in item 3.1 in Table 11 can be found from the formula

$$N_{\gamma f}^8 = N^{\rm FR} \, \frac{\varepsilon_{\gamma f}^8}{\varepsilon_{\rm tr}^{\rm FR}} \,, \tag{27}$$

where $\varepsilon_{\gamma f}^8$ and $\varepsilon_{\rm tr}^{\rm FR}$ are the efficiency of the photofission channel and the efficiency of transmutation of a fission nuclide (the latter efficiency is averaged over the channels).

The photoneutrons absorbed by the nuclei of transuranium actinides and ^{238}U (see item 2.4 in Table 11) is the cause of fission of the latter. The number of nuclei $N_{\rm nf}^{\rm TA+8}$ fissioned by these neutrons (see item 3.2 in Table 11) can be estimated by the following formula

$$N_{\rm nf}^{\rm TA+8} = N_{\gamma n}^{\rm f} = N_{\gamma n}^{\rm a} \, \frac{\sigma_{\rm f}^{\rm TA+8}}{\sigma_{\rm f}^{\rm TA+8} + \sigma_{\rm c}^{\rm TA+8} + \sigma_{\rm out}^{\rm TA+8}} \,, \tag{28}$$

where $N_{\gamma n}^{\rm f}$ is the number of photoneutrons causing fission, and $\sigma_{\rm out}^{\rm TA+8}$ is the cross section of 'shifting' fast neutrons into an energy range below the fission threshold for ^{238}U and transuranium nuclides, averaged over the fission spectrum and nuclide concentrations.

To fission all nuclei of ^{238}U and TAs, the strength of the fast-neutron source should be increased K-fold, i.e., subcritical fast-neutron multiplication must be implemented in the target – blanket system with an effective multiplication factor $K_{\rm eff}$:

$$K = \frac{1}{1 - K_{\rm eff}} = \frac{N^{\rm TA+8} - N_{\gamma f}^8}{N_{\rm nf}^{\rm TA+8}} \,. \tag{29}$$

The number of fast neutrons $N_{\rm fn}^{\rm B}$ produced in the blanket as a result of multiplication can be found from the expression

$$N_{\rm fn}^{\rm B} = N_{\rm fn}^{\rm TA+8} = (\langle \eta \rangle^{\rm TA+8} - 1)(N^{\rm TA+8} - N_{\gamma f}^8) \,, \tag{30}$$

where

$$\langle \eta \rangle^{\rm TA+8} = \langle \nu \rangle^{\rm TA+8} \, \frac{\sigma_{\rm f}^{\rm TA+8}}{\sigma_{\rm f}^{\rm TA+8} + \sigma_{\rm c}^{\rm TA+8} + \sigma_{\rm out}^{\rm TA+8}} \,. \tag{31}$$

The number of neutrons absorbed by the regenerated uranium in their deceleration from the energy $E_n \simeq 100$ keV to resonance energies and in the resonance-absorption range $E_n \leqslant 200$ eV is determined by the neutron utilization factors f and f_r, respectively (see items 4.1 and 4.2 in Table 11), each of which is determined by the formula

$$f = \frac{N^U \sigma_c^U}{N^U \sigma_c^U + N^{TA+8}(\sigma_c^{TA+8} + \sigma_f^{TA+8})}, \quad (32)$$

where N^U is the total number of nuclei of the regenerated uranium in the peripheral zone of the blankets, and N^{TA+8} is the total number of nuclei of TAs and depleted ^{238}U placed within the blanket CZ, with the capture and fission cross sections averaged over the above-noted neutron energy ranges.

The number of fissile (breeding) nuclei, N_{br}^9, produced in the regenerated uranium as a result of neutron capture and the conversion ratio BR are given by the following expressions

$$N_{br}^9 \simeq \langle f \rangle N_n^\Sigma, \qquad BR = \frac{N_{br}^9}{N_f^5}, \quad (33)$$

where $\langle f \rangle$ is the average value of the utilization factor in the above-noted neutron energy range, N_n^Σ is the total number of neutrons in the target–blanket system (see item 3.5 in Table 11), and N_f^5 is the number of ^{235}U nuclei burnt up in the previous campaign period (see item 1.1 in Table 11).

The data listed in Table 11 suggest that, within the accuracy of the data on ^{235}U burn-up and nuclide content in SNF, complete conversion of fissile nuclei can be achieved in conditions of deep subcriticality of the blankets combined with full compensation for the energy inputs needed to generate gamma radiation of the intensity required. As the amount of ^{238}U in the central zone of the blankets grows and K_{eff} increases, the energy output in the blankets may exceed the energy input needed for transmutation and conversion. For instance, if the ^{238}U nucleus content is increased by 50%, K_{eff} grows to 0.95, BR remains practically the same, and the energy output in the blankets exceeds the energy input needed for transmutation by roughly 15% of the energy output of NPP units involved in the cycle.

5.6 Productivity

The required intensity of gamma radiation is determined by the condition that the nuclides subjected to transmutation must not accumulate: the ^{90}Sr and ^{137}Cs nuclei that do have not absorbed neutrons must be transmuted by gamma quanta in the campaign period T_c of the VVR-1000 reactor. Hence, the intensity $\dot{N}_\gamma^T$ of the beam of gamma quanta incident on a target must obey the relation

$$\dot{N}_\gamma^T = \frac{\dot{N}_{tr}}{m\varepsilon_{tr}} = \frac{N^{^{90}Sr+^{137}Cs}}{mT_c\varepsilon_{tr}}, \quad (34)$$

where $N^{^{90}Sr+^{137}Cs}$ is the total number of ^{90}Sr and ^{137}Cs nuclei contained in the SNF of the reactor, ε_{tr} is the total efficiency of the gamma-transmutation channels, taken from Table 10, and m is the number of targets containing the transmutable nuclides. Of course, the $\dot{N}_\gamma^T$ obtained in this manner is overvalued because ε_{tr} was determined in an approximation of a single interaction between the incident gamma quanta and target and with undervalued photonuclear cross sections. The exact solution of the problem requires knowing the cross sections of the transmutable radionuclides, measured in beams of synchrotron or undulator radiation rather than traditional bremsstrahlung which differs significantly from the former in that the contribution of the dipole component is undervalued. Basing our reasoning on Wolynec's paper [25], we can state that with fully dipole radiation, such as synchrotron radiation and, even more so, undulator radiation, we would expect an increase in the yield of gamma-transmutation products by a factor of almost two and, respectively, a decrease in the expenditure of energy and the required intensity $\dot{N}_\gamma^T$ of the same proportion. Earlier we stressed the need to take into account multiple processes in the targets.

An intensity of gamma radiation close to the required value can be achieved even with the electron storage rings that are currently in operation. For instance, at the Brookhaven National Laboratory (USA), a source of synchrotron radiation with $E_e = 3$ GeV and an electron current of 2.5 A has been in operation for several years [18]. In Hamburg (Germany) and at CERN (Switzerland and France), HERA and LEP storage rings with energies of 50 and 100 GeV, respectively, with the average electron current in the first being as high as 50 mA, have been in operation for many years [17]. They are employed as electron–positron colliders in high-energy physics studies in which synchrotron radiation is parasitic, and so a high average current was not a priority for the designers of these rings.

All this suggests that both modes of generation of gamma radiation guarantee parameters of electron beams that ensure the required intensity of nuclide transmutation and conversion. With 4-GeV electrons, the length of the orbit in the accelerator amounts to 400–600 m, while for 80-GeV electrons this figure reaches a value of 12–15 km. As noted earlier, with such long orbits it is possible to have many straight sections for residing emitting structures, while the targets and blankets can be located on the extensions of their axes.

The logical way to implement the electrophotonuclear power cycle within the industrial zone of an operating NPP is to remain within this zone. This would make it possible to avoid problems with transporting, storing, and handling SNF, HRW, and fissionable materials outside the borders of the NPPs, which would increase the safety of using nuclear power. At BR = 1, each such nuclear energy-generating system can be considered self-sustained and meeting the criteria of natural safety.

An electron storage ring with $E_e \sim 4$ GeV and insert emitting devices $n = km$ (k is the number of units within the NPP area, and $m = 3$–4 is the number of target–blanket systems capable of supporting a single NPP unit in one campaign period) would be sufficient as an accelerator. The required intensity of gamma radiation, determined by condition (34) with $\varepsilon_{tr}^{FR} \sim 0.1$ and $m = 4$, must be $\dot{N}_\gamma^T \sim 2 \times 10^{19}$ photons per second. Such intensity can be achieved with an electron current in the storage ring of about 2.5–5 A, and a radiation flux density of a pulsed carbon-dioxide laser $P \simeq 5 \times 10^{11}$ W cm^{-2} focused on the length of interaction with the electron beam that is about 4 m (see an example of the calculation in Ref. [16]).

It is advisable to use a storage ring of the accelerator with $E_e \sim 80$ GeV and superconducting wigglers with $H_0 \sim 4$ T as generators of gamma radiation if electrophotonuclear technology is to be implemented together with a large-scale

radiochemical facility for reprocessing SNF. This variant would be especially important if it was used to reprocess not only the SNF from the national NPPs but also the fuel unloaded from mobile nuclear power plants.

6. Conclusions

We have arrived at the following conclusions:

(1) Of the radionuclides contained in SNF and HRW, ^{90}Sr and ^{137}Cs present the greatest danger, while the most dangerous of the transuranium actinides is the ^{241}Pu – ^{241}Am pair since, contrary to the opinion expressed by specialists in nuclear reactors, the former do not decay but accumulate and soon (by 2020 – 2025) will reach an equilibrium, creating together with the latter an unacceptably high level of radioactivity close to 620 MCi GW(el.)$^{-1}$ and radiotoxicity outside NPP storage facilities, which will be retained in the environment for the entire time of operation of the nuclear power industry.

(2) The burial and/or terrestrial controllable storage of SNF and HRW do not exclude long-term radiation-associated risks. A consistent solution to the problem can be found only by applying nuclear-physical principles, methods, and means, which will make it possible to remove the primary reason for these risks — the above-mentioned radionuclides.

(3) The approaches that have been developed lately do not completely solve the problems of nuclear power cycle since, being unable to transmute the above-named fission products, they preserve the back end of the cycle unchanged, thus creating no "structural economy" and, therefore, are both ecologically and economically untenable.

(4) The problem can be radically solved by the gamma – neutron transmutation method which makes it possible, by augmenting the traditional fission process by other electro-, photo-, and neutron-physical processes, to realize the concept by which uranium and the most dangerous products of the fission process circulate, so to say, in a closed cycle, with the latter used as sources of neutrons for reproducing the power-generating potential of the former, and only stable isotopes and low-activity radionuclides reach the environment. This would make it possible to

(a) lower the activity of NPP wastes buried and stored by a factor of 100 000;

(b) increase the number of recycles of uranium as fuel for NPPs by a factor of 30;

(c) completely compensate for the energy inputs intended for nuclide transmutation and conversion, and

(d) convert fissile fuel without employing enrichment in ^{235}U and without the use of pure plutonium, which technologically would guarantee nonproliferation of enriched fissionable materials.

Each NPP included in such an electrophotonuclear power cycle could function as a sustainable nuclear power system and would meet the criteria of nature safety, since the activity of the buried radioactive waste would be comparable to the activity of the mined natural uranium circulating in the cycle.

(5) The above implies that an electrophotonuclear power cycle involving power-generating thermal-neutron reactors can ensure complete conversion of fissile fuel, with the result that the strategy of transferring the nuclear power industry to breeder reactors seems to have an alternative, contrary to the belief of the designers of that strategy [26].

(6) An increase in the effectiveness of using mined uranium and the inclusion in the fuel cycle of depleted uranium, hundreds of thousands of tons of which are stored as uranium reject at isotope-separation plants, would reduce the demand for natural uranium and the ecological damage inflicted by field development.

(7) The transmutation of ^{90}Sr and ^{137}Cs nuclides and the destruction of transuranium nuclides at the back end of the open fuel cycle results in structural economy which, with the additional cost of the convertible fuel, amounts to roughly 50% of the cost of the fuel cycle, which is much higher than the expenditures on the nuclide transmutation and conversion.

Thus, the physical completeness and ecological efficiency of the method make the implementation of the proposed concept cost-effective. As a result, the volume of unprocessed SNF can be markedly reduced and the nuclear power cycle can become more clean, economical, and safe.

The possibility of task-oriented transmutation of radionuclides present in SNF into stable isotopes was first discussed in 1984 already with P É Nemirovskiĭ and later with V I Mostovoĭ, including participation in his seminar 'Nuclear physics of the nuclear power industry' which was held at the I V Kurchatov Institute of Atomic Energy.

In view of the distinct interdisciplinary nature of the problem, the individual aspects of its solution have been discussed over the years with a number of scientists and specialists in radiochemistry (V I Volk), nuclear physics (A L Barabanov, D F Zaretskiĭ, and É E Sapershteĭn), the physics and technology of accelerators (A N Skrinskiĭ, G N Kulipanov, A G Valentinov, and L A Yudin), laser-optical systems (D D Malyuta, Yu A Satov, and A N Starostin), laser isotope separation (I S Grigor'ev and V A Firsov), the physics of electromagnetic and photonuclear interactions (B S Ishkhanov and V V Varlamov), the neutron physics of multiplying and moderating media (L V Maĭorov and M S Yudkevich), and the physics of nuclear reactors (V V Orlov, S D Malkin, E V Burlakov, N I Laletin, and D M Petrunin). I am grateful to the above individuals for their interest in the problem of transmutation of radionuclides and for their useful remarks made in the numerous discussions.

Obviously, the solution to such a problem in full is possible only by a specialized organization. Unfortunately, the absence of any support in the course of many years from the RF Ministry of Science and the direct opposition of the RF Ministry of Atomic Industry (E O Adamov, Yu A Sokolov, N S Rabotnov, A Yu Rumyantsev, and M I Solonin) and of several members of the Presidium of the Russian Academy of Sciences (B F Myasoedov) have made such an R&D body impossible. I was forced to solve this problem by myself and to work only on a voluntary basis. Therefore, I am extremely grateful to N D Bondarev and S S Yakimov for organizational support within their powers, and to A V Inyushkin and Yu V Kononets for technical support.

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