Physics – Uspekhi **46** (7) 717 – 723 (2003)

INSTRUMENTS AND METHODS OF INVESTIGATION PACS numbers: 28.41.Bm, **28.50. – k**, 89.30.Gg

Radiation safety in the Russian atomic power industry

A S Gerasimov, G V Kiselev

DOI: 10.1070/PU2003v046n07ABEH001386

Contents

Abstract. Of all the radioactive wastes known in nuclear power industry and engineering, long-lived actinides and fission products from spent nuclear fuel are the most hazardous. One way to reduce their radiation hazard is to resort to nuclear transmutation, which can be performed either in reactors of various types or in accelerator-driven subcritical systems, whose nuclear safety is superior to that of conventional reactors. Fundamentally resolving the problem of the destruction of long-lived radioactive wastes is likely to stimulate progress in the development of the nuclear power industry.

1. Introduction

U.S. Surgeon General's warning: smoking causes lung cancer, heart disease, emphysema, and may complicate pregnancy. Tobacco seriously damages health! Specialists have calculated that a person who smokes two packs of cigarettes receives a daily radiation dose. In the U.S. alone smoking kills about 100,000 people every year. And how many people die from the effects of the nuclear power industry and engineering? It is understood that potentially the nuclear power industry and engineering are much more dangerous than smoking, especially in critical situations such as the Chernobyl accident, when the radiation hazard becomes incompatible with the lives of a large number of people. After the Chernobyl accident, the measures taken to ensure the safe operation of nuclear power plants were unprecedented — in no other industry are the safety measures so strict as in the nuclear power industry. The present article is an attempt to analyze the problems of radiation safety in the nuclear power industry today and in the future, and the possible measures that must be taken to ensure greater safety. This topic has been thoroughly covered in a large number of papers and reports by Russian and foreign specialists, but we hope that our ideas are of interest also to nonspecialists in the field of nuclear power production.

A S Gerasimov, G V Kiselev Russian Federation State Scientific Center 'Institute for Theoretical and Experimental Physics'
B. Cheremushkinskaya ul. 25, 117259 Moscow, Russian Federation
Tel./Fax (7-095) 129 97 03, 127 05 43
E-mail: geras@vitep1.itep.ru; kiselev_g@vitep1.itep.ru

Received 3 April 2003
Uspekhi Fizicheskikh Nauk **173** (7) 739 – 746 (2003)
Translated by E Yankovsky; edited by A Radzig

2. Radioactive wastes

Radioactive wastes are long-lived radioactive nuclides produced by the operation of nuclear power plants. Such fission fragments are assumed to have no practical use and are potentially hazardous to the environment.

The most dangerous radioactive wastes from nuclear power plants are those known as high-level radioactive wastes, which comprise minor actinides (MA) and long-lived fission fragments (FF) that accumulate in nuclear fuel with operation of nuclear reactors. Freshly unloaded nuclear fuel is highly radioactive due to the presence of short-lived fission fragments. After the spent nuclear fuel (SNF) has been unloaded from the reactor, it is kept for several years in a special repository for intermediate ageing (or 'cooling'), so that the short-lived FF have time to decay, with the result that the radioactivity of the SNF considerably decreases. Then the SNF is moved to another repository, where it is either subjected to chemical reprocessing or is kept in storage in less stringent conditions.

The long-lived FF are dangerous because of the gamma radiation they give off, which accompanies beta decay. Incidentally, beta radiation is also dangerous for the human (and not only for the human) body. Long-lived actinides are highly dangerous because of emitting alpha particles. In a separate group one should place isotopes of plutonium, which accumulate in the fuel of nuclear reactors. In prospect plutonium will be used as fuel in nuclear power plants. Hence, from the viewpoint of handling radioactive wastes, neptunium, americium, and curium are usually considered

the minor actinides, while uranium and plutonium do not belong to that class of actinides. The proportions of the main long-lived actinides and the fission fragments in the SNF of nuclear power reactors and the respective half-lives are listed in Table 1 [1].

Table 1. Abundance (g/t) of long-lived fission fragments and actinides in the SNF of the VVÉR-1000 and RBMK-1000 reactors with a 0.5-year ageing period.

Nuclide	$T_{1/2}$, yr	VVÉR	RBMK	Nuclide	$T_{1/2}$, yr	VVÉR	RBMK
^{79}Se	6.5×10^4	5.9	3.5	^{237}Np	2.14×10^6	620	150
^{90}Sr	29.2	680	390	^{238}Pu	86.96	126	69
^{93}Zr	1.5×10^6	910	530	^{239}Pu	2.4×10^4	5330	2630
^{99}Tc	2.13×10^5	950	600	^{240}Pu	6.57×10^3	2420	2190
^{107}Pd	6.5×10^6	250	200	^{241}Pu	14.38	1470	710
^{126}Sn	10^5	22	15	^{242}Pu	3.76×10^5	580	510
^{129}I	1.6×10^7	220	140	^{241}Am	432.2	72	36
^{135}Cs	2.3×10^6	420	220	^{243}Am	4.35×10^3	120	74
^{137}Cs	30	1460	900	^{242}Cm	0.442	6.1	5.2
^{151}Sm	90	15	4.0	^{244}Cm	18.1	46	8.1

Note: VVÉR-1000 is a Russian abbreviation of a 1000 MW water-moderated water-cooled power reactor, and RBMK-1000 is a Russian transliteration of a 1000 MW high-power channel-type reactor.

The common characteristic of the radioactivity of nuclides is the activity equal to the number of decays per unit time. A more informative characteristic (compared to activity) of the radiobiological hazard presented by radionuclides is radiotoxicity, since it takes into account the effect of the radiation from specific nuclides on the human body. For an individual nuclide i, the radiotoxicity RT_i by respiration or by ingestion is given by the formula

$$\mathrm{RT}_i = \frac{\mathrm{A}_i}{\mathrm{PA}_i},$$

where A_i is the activity of the considered amount of nuclide i, and PA_i is the permissible activity of this nuclide in air or water specified by the Radiation Safety Standards [2]. The total radiotoxicity is the sum of the radiotoxicities of all the nuclides in the amounts in which they are present in the mixture considered.

Figure 1 shows the total radiotoxicity by ingestion of the minor actinides that are in prolonged storage and the relative contributions from different nuclides to this quantity, while Fig. 2 depicts the same pattern for the long-lived fission fragments [3, 4]. The broad range of storage times T in Figs 1 and 2 may, at least in principle, include the time of final underground disposal. The data refer to nuclides extracted from 1 t of SNF of the VVÉR-1000 reactor after three years of intermediate ageing.

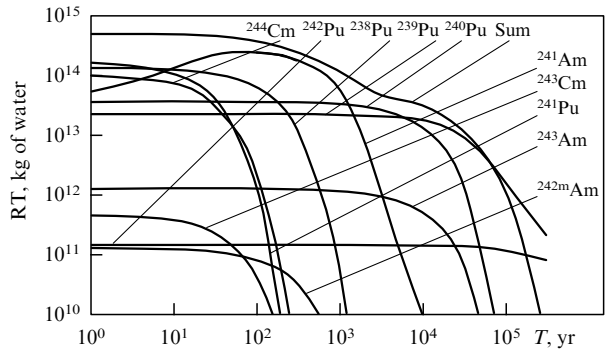

Figure 1. Radiotoxicity by ingestion of the minor actinides extracted from 1 t of SNF in prolonged storage.

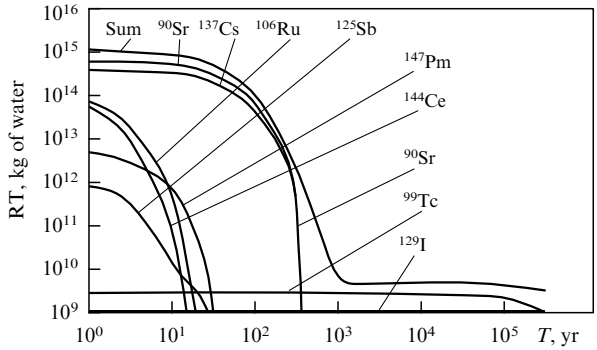

Figure 2. Radiotoxicity by ingestion of long-lived fission fragments extracted from 1 t of SNF in prolonged storage.

When the storage time amounts to several dozen years, the total radiotoxicity by ingestion is determined by the fission fragments, among which ^{90}Sr and ^{137}Cs are especially prominent (the two have a half-life of about 30 years). Under further storage, the contribution from the fission fragments to the radiotoxicity rapidly decreases, while the radiotoxicity of actinides decreases gradually. For storage times amounting to one century, the contribution of the fission products to the total radiotoxicity is 20%, while for storage times amounting to three centuries it is 0.35%. Note that if we take the radiotoxicity by respiration (which is determined by the permissible activities of hazardous nuclides in air) as the criterion, at the very beginning of storage the radiotoxicity of the actinides is much higher than that of the long-lived fission fragments.

The radiotoxicity of actinides for storage times of up to ten years is determined by the nuclides ^{244}Cm, ^{241}Pu, and ^{238}Pu, up to one century by ^{241}Am, up to 3000 years by ^{240}Pu, and greater than 30,000 years by ^{239}Pu. The radiotoxicity of the fission fragments rapidly decreases after the decay of ^{90}Sr and ^{137}Cs, and after 300 years of storage it is determined by the ^{99}Tc and ^{129}I nuclides.

3. Strategy of development of the nuclear power industry in Russia

In May 2000, the government of Russia approved the "Strategy of development of the nuclear power industry in Russia in the first half of the 21st century", which was developed and presented by the Russian Federation Atomic Energy Ministry [5]. The development of nuclear power plants will proceed in two stages, with the total electric power of the nuclear plants brought up to 60 GW by the year 2030:

— the first stage, which is being currently implemented, amounts to developing atomic power plants that use thermal neutron reactors and accumulating plutonium for start-up and parallel development of fast neutron reactors;

— the second stage will amount to the development of nuclear power plants on a broad scale, which will mostly be fast reactors. These will gradually replace the conventional power plants operating on fossil fuels.

However, in the decades to come Russia's nuclear power-generating industry will be, due to financial difficulties, largely a single-component industry, primarily using thermal neutron reactors, with a small percentage of fast reactors.

Today Russia has in operation 29 nuclear power reactors with a total output electric power of 21.2 GW. Among these are 13 power-generating units with VVÉR reactors, 11 power-generating units with RBMK reactors, 4 EGP power-generating units of the Bilibino nuclear central heating and power plant with water – graphite channel-type reactors, and 1 power-generating unit with a BN-600 fast neutron reactor. Still operating are the industrial uranium – graphite reactors in Seversk (the Siberian Nuclear Power Plant) and in Zheleznogorsk. Practically ready for start-up are five power-generating units with VVÉR-1000 reactors and one unit with an RBMK reactor.

Among the reactors of the new generation are the BREST-300 and BREST-1200 fast neutron lead-cooled reactors. The motto of the "Strategy" is *the safer the cheaper* rather than *the more expensive the safer*.

A promising area in the strategy is the passage to closed fuel cycle, in which the natural nuclear fuel and the artificial fissionable materials produced as a result of the operation of reactors (plutonium and the like) can be used more fully. As pointed out in the "Strategy", the utilization of weapon plutonium must be considered only as the first stage in the building of the future technology of a closed nuclear fuel cycle. A technologically and economically sound method of utilizing weapon plutonium can be implemented only after the BN-800 and BREST-1200 fast neutron reactors become operational.

This leads to an increase, first, in the initial charge of the plutonium fuel in the reactors and, second, in the amount of highly active long-lived fission fragments and minor actinides produced. For instance, the specific charge of the fissionable materials (a mixture of nitrides of uranium and plutonium) for the BREST-300 reactor is 1.9 times larger than that for the BN-800 reactor. The burn-up fraction of the nuclear fuel in fast reactors is approximately 100,000 MW day/t, which is 2 – 2.5 times greater than in thermal neutron reactors. This leads to a respective increase in the FF and MA buildup both in the reactor core and in the SNF. Today Russia has about 14,000 t of SNF with a total activity of about 5×10^9 Cu.

As pointed out in the "Strategy", in the future it is advisable to perform, in the two-component structure of the nuclear power engineering, a gradual changer-over of thermal neutron reactors to the thorium fuel cycle, in which the production of plutonium, americium, and curium is much lower than in the uranium or uranium – plutonium fuel [6 – 8]. The plan is to build a demonstration power-generating unit at a nuclear power plant with a thermal reactor in the Th – U cycle and by the year 2050 to make this experimental facility operational.

Table 2 gives a rough idea of the relative radiobiological hazards of the SNF in a simple open fuel cycle. The table lists the calculated estimates of radiotoxicity by ingestion for long-lived actinides and fission fragments extracted from 1 t of spent uranium, uranium – plutonium, and thorium – uranium nuclear fuels of the VVÉR power reactors [3, 4].

One of the possible ways of reducing the radiobiological hazard of nuclear power plants is to use the transmutation of long-lived radioactive wastes, which will become an integral part of the nuclear fuel cycle [5].

Table 2. Radiotoxicity by ingestion (in 10^{14} kg of water) of long-lived actinides and fission fragments extracted from 1 t of spent uranium, uranium – plutonium, and thorium – uranium nuclear fuels.

Storage time, yr	Actinides			Fission fragments
	Uranium	Uranium – plutonium	Thorium – uranium	
10	5.0	12	1.4	8.2
100	3.7	9	0.6	1.0
1000	1.2	3	0.005	5×10^{-5}

4. Transmutation of radioactive wastes

Nuclear transmutation consists of the transformation of long-lived radionuclides into short-lived or stable nuclides via neutron irradiation in nuclear facilities (reactors, etc.). The goal of transmutation is to considerably reduce the amount and radiobiological hazard of the radioactive wastes and facilitate their final underground disposal.

First we must answer the following questions: Why is transmutation needed in general? Why can we not just store the radioactive waste for a very long time or give it a final geological burial? There is no single answer to these questions and, if we put aside the political aspects, they depend primarily on the current advancement of technology.

Every repository used to store ecologically hazardous materials is potentially, to one extent or another, a threat to the environment. Long-term underground storage of radioactive waste assumes the existence of a repository specially designed and controlled in such a way that normal pressure and temperature are maintained at all times and the safety is constantly monitored.

Transmutation presupposes that long-lived wastes will be in the fuel cycle of the transmutation installations in extreme conditions, at high temperatures and under high pressures and in a highly aggressive environment. There must be a really valid reason for transmutation, since it means a rise in the risk of ecological contamination by the radioactive wastes in the transmutation installations. And the reason is the considerable increase in environmental safety in the future, for a period of several dozen thousand years and more.

The buildup of radioactive waste because of the operation of nuclear power plants goes on steadily. The disposal of these wastes can be done in different ways depending on the problems that confront us. In one possible approach, transmutation serves as a means for destroying the wastes that have accumulated during the entire period in which atomic power plants have been operating. Here, the transmutation installations are incorporated at the final stages of the era of the nuclear energy and have no effect on the buildup and storage of wastes at the intermediate stages. According to another approach, transmutation must operate constantly, together with the functioning of the nuclear power-generating industry. In this case, lowering the general level of wastes being constantly produced in the industry and facilitating the storage of such wastes are needed.

A transmutation installation is a nuclear reactor, a subcritical accelerator-driven system (ADS), or a facility of another type whose main goal is to produce neutrons and to ensure that they are absorbed by the materials undergoing transmutation.

Transmutation is effective if it is done in the conditions when a periodical supplementary charge of the transmutable

material takes place in lieu of the material destroyed. Recharging in transmutation installations with solid fuel replaces the nuclear fuel and, at the same time, makes it possible to reprocess and decontaminate the irradiated materials from the transmutation products. On the other hand, in transmutation installations with liquid fuel and liquid transmutable materials, the chemical reprocessing, decontamination, and addition can be done continuously by extracting a fraction of the liquid substance into a special contour and subsequently returning it to the installation.

Below we discuss the transmutation of the most hazardous radioactive wastes, namely, the minor actinides and the long-lived fission fragments from the SNF. Transmutation of fission fragments proceeds by (n, γ) reactions, while transmutation of actinides proceeds by the fission reaction. These processes run differently, each having its own specific features, so that it is advisable to examine them separately.

5. Transmutation of long-lived fission fragments

The transmutation of fission fragments usually reduces to transformation of an original radioactive long-lived nucleus into the neighboring stable or short-lived nucleus by the (n, γ) reaction or a similar reaction not related to fission.

The main characteristics of the process of transmutation of fission fragments are the reaction rate and the transmutation productivity. The transmutation rate is equal to the product of the effective cross section of the (n, γ) reaction by the neutron flux density. It determines the fraction of nuclei that have been transmuted in a certain time interval (when the reaction rate is constant, the number of the mother nuclei remained decreases exponentially, so that in a finite time interval a given number of radionuclides are never transmuted completely).

For instance, in the transmutation of ^{99}Tc in a light-water nuclear reactor with a neutron flux density of 10^{14} neutrons per square centimeter per second, which is a characteristic figure for research reactors, after one year of irradiation 61% of ^{99}Tc nuclei still remain in their initial state, i.e., 39% of the nuclei have been transmuted. The ^{129}I nuclei exhibit similar behavior: after a year of irradiation 87.7% of such nuclei remain intact, i.e., 12.3% ^{129}I have been transmuted. Both factors, the neutron flux density and the effective reaction cross section, play an important role in increasing the reaction rate. For instance, in a high-flux heavy-water reactor with a neutron flux density that is ten times higher, 10^{15} neutrons per square centimeter per second, the transmutation rate of ^{99}Tc is only 3.5 times higher, since in the soft neutron spectrum of the heavy-water nuclear reactor the effective cross section of ^{99}Tc transmutation is smaller by a factor of 2.9 than in the spectrum of a light-water reactor, with a substantial fraction of epithermal neutrons.

The highest transmutation rate that can be attained in modern nuclear reactors for the transmutation of the most environmentally dangerous fission products, ^{90}Sr and ^{137}Cs, which have a half-life of about 30 years and a very low neutron-capture cross section, has proven to be lower than the natural decay rate. Thus, specialists agree that it is practically impossible to achieve transmutation of ^{90}Sr and ^{137}Cs by currently available methods.

The productivity of a transmutation facility is the mass of radionuclides destroyed per unit time. It is proportional to the number of free neutrons and, eventually, to the output power of the facility. For nuclear reactors, the proportionality factor depends on how many neutrons can be used for transmutation per single fission act of the nuclear fuel. In properly designed research or specialized reactors intended for the production of useful nuclides, approximately one neutron in every fission act can be used for transmutation. If ^{99}Tc and ^{129}I are to be transmuted with a productivity equal to the average rate of their production in VVÉR power reactors, the output power of transmutation reactors must amount to approximately 8% of the total output power of the VVÉR reactors.

The following processes complicate the transmutation of fission fragments:

— neutrons are absorbed in the nuclides being destroyed, in other isotopes of the same chemical element, and in daughter nuclides;

— new long-lived fission fragments are produced in the nuclear fuel of the transmutation reactors proper.

What effect do these side processes have? In the common approach, a sample intended for transmutation and containing the harmful isotope together with other isotopes of the same chemical element is charged into the facility. All the isotopes present in the sample are irradiated with neutrons. If the harmful isotope absorbs almost all the neutrons, the consumption of neutrons that go to destroying a single harmful isotope is not much greater than unity. However, if the amount of the harmful isotope or the isotope's neutron-absorption cross section is much smaller than the amount or neutron absorption cross section of the other isotopes, the consumption of neutrons increases substantially. For instance, destroying a single ^{93}Zr nucleus and simultaneously irradiating the other stable zirconium isotopes, ^{90}Zr, ^{91}Zr, ^{92}Zr, ^{94}Zr, and ^{96}Zr, requires about a hundred neutrons. This effect reduces transmutation productivity. Theoretically, it is very easy to neutralize the above effect, but technologically this is a complicated process involving the separation of the harmful isotope from the other isotopes prior to transmutation.

New radioactive fission fragments are produced in the fuel of transmutation reactors proper because the reactor must generate neutrons for the transmutation process, and these neutrons can be obtained only via fission. But if instead of a nuclear reactor we take a transmutation ADS in which the neutrons are generated in a neutron-producing target irradiated with protons from an accelerator, no new fission fragments are produced in the facility proper. One must bear in mind, however, that electric energy is needed to energize the accelerator, and so transmutation ADS facilities should be included in the energy balance of the nuclear power-generating industry. The electric energy is generated at an atomic power plant. The result is that the fission fragments accompanying transmutation in the ADS in question are produced in the nuclear fuel of this power plant. A detailed balance between the radioactivities of the destroyed and produced nuclides has been struck in Ref. [9]. Secondary radioactivity of the newly produced nuclides is much higher than the radioactivity of the nuclides destroyed. However, for a meaningful interpretation of the results one must bear in mind that secondary radioactivity is primarily determined by the ^{90}Sr and ^{137}Cs nuclei, while the nuclides destroyed have half-lives ranging from hundreds of thousands of years to millions of years. If we limit ourselves to transmutation of the most important highly long-lived ^{99}Tc and ^{129}I nuclei, the secondary radioactivity of the newly produced fission fragments, mostly ^{90}Sr and ^{137}Cs, amounts to 10 – 12% of the

radioactivity of ^{90}Sr and ^{137}Cs that are already in the SNF. In the transmutation of ^{151}Sm, ^{93}Zr, and ^{126}Sn, which requires very high neutron consumption, secondary radioactivity is significant.

In prolonged continuous transmutation, neutrons are captured by the daughter products of transmutation and new nuclides are produced in succession, and some of these nuclides may be radioactive. For instance, long-lived ^{107}Pd is produced during deep transmutation of ^{99}Tc (a reduction of radioactivity by a factor of 100) with eightfold neutron capture, while ^{135}Cs is produced (true, in scarcely detectable quantities) during transmutation of ^{129}I with sevenfold neutron capture. This can be avoided if periodic decontamination from transmutation products is done.

Can fission fragments be directly transmuted in a nuclear power reactor? Placing targets with absorbing nuclides in a power reactor lowers its reactivity and reduces the fuel residence time. For instance, if ^{99}Tc and ^{129}I are being transmuted in a VVÉR reactor at a rate equal to that of their buildup, the fuel residence time and the energy production decrease by 12% [10]. These results suggest that attempts at transmutation of fission fragments in power-generating reactors will lead to unreasonably high losses in energy production. Specialized transmutation facilities should be used for transmutation.

Can all hazardous long-lived fission fragments be transmuted? At present the international scientific community is rather pessimistic on this matter. Owing to the large number of neutrons needed to destroy ^{93}Zr, ^{107}Pd, ^{126}Sn, and ^{151}Sm, the transmutation of these nuclei in nuclear reactors is hardly possible. A breakthrough in this area may be achieved by using installations of a new type based on other ways of producing neutrons, ways that do not involve fission reactions [11].

6. Transmutation of actinides

The transmutation of actinides proceeds by fission reaction and differs substantially from the transmutation of fission fragments. The main difference is that fission fragments transform into stable nuclides, whereas actinides transform into other actinides and, finally, into fission fragments. There are two important features in the actinide transmutation process.

First, the fission of actinides occurs differently in the thermal and fast spectra. In the thermal spectrum, ^{239}Pu, ^{241}Pu, ^{242}Am (short-lived), ^{243}Cm, and ^{245}Cm are the fissionable nuclei. In the fast spectrum, all actinides are fissionable, but the cross sections of the (n, γ) reactions are of the same order of magnitude as the fission cross sections.

Second, both in the thermal spectrum and in the fast spectrum, highly radiotoxic ^{238}Pu and ^{244}Cm isotopes are produced under irradiation by the following reactions:

in the transmutation of neptunium

$$^{237}Np + n \rightarrow {}^{238}Np(\beta, 2.12\ d)\,{}^{238}Pu\,,$$

and in the transmutation of americium

$$^{241}Am + n \rightarrow {}^{242}Am^{g}(\beta, 16\ h)\,{}^{242}Cm(\beta, 161\ d)\,{}^{238}Pu\,,$$
$$^{243}Am + n \rightarrow {}^{244}Am(\beta, 10\ h)\,{}^{244}Cm\,.$$

In the transmutation of minor actinides without the addition of new actinides, these processes lead to an increase in radiotoxicity during a certain period of time; then the radiotoxicity drops to the initial values and decreases even below these values. The time it takes the radiotoxicity to increase and then decrease to the initial values amounts to about 10 years for thermal nuclear reactors, and 20 years for fast reactors [12, 13].

It is assumed that in reality the transmutation process will periodically be stopped so that new actinides may be added, the accumulated fission fragments can be extracted, and supplementary charge of fresh nuclear fuel may be executed, while the remaining actinides will be returned for further transmutation. Then, in the transmutation reactor the radiotoxicity of the actinides will grow up to a certain asymptotic level, which is determined by the rates of nuclide transformation reactions.

7. Neutron spectrum for actinide transmutation

The main problem in actinide transmutation is the choice of the proper irradiation conditions most suitable for the transmutation of actinides. At present many specialists in nuclear reactor problems believe that the fast spectrum is preferable because all actinides are fissionable in it [14]. This spectrum is good from the viewpoint of the neutron balance in the transmutation reactor, where there is no need to charge a large amount of nuclear fuel for the production of neutrons.

However, transmutation can also be effectively achieved in facilities with a thermal spectrum and a high neutron flux, which ensures high reaction rates for the transformation of nuclides.

Owing to the buildup of ^{238}Pu and ^{244}Cm isotopes and other dangerous actinides, nuclear transmutation facilities have become a kind of storage for sources of long-lived radiotoxicity. In this situation it is advisable to compare facilities of different types not only from the neutron-balance viewpoint but also by the characteristics related to the radiotoxicity of the transmutable actinides.

Such comparisons have been carried out in Refs [15–18, 13] for different types of transmutation facilities and the radiation safety standards that existed in different periods. Here are the most recent results taken from Ref. [13]. The researchers used the data on the following power-generating reactors acting as transmutation reactors: VVÉR-1000, the Canadian heavy-water reactor CANDU, the French fast reactor 'SuperPhoenix', and the fast reactor BREST-1000 that is being currently developed [19]. In addition, they also used the data on the subcritical high-flux accelerator-driven system ELYaU-800 operating on thermal neutrons (the design characteristics of this installation can be found in Ref. [20]). The model used to describe the transmutation process was that of continuous irradiation in neutron fluxes and spectra that existed in the nuclear fuel of the transmutation reactors, with continuous addition of new actinides for transmutation. Such a simplified model allows the quantitative comparison between transmutation efficiencies relevant to various installations operating under conditions of a closed fuel cycle to be drawn in a simple and self-evident manner. The continuous irradiation model is actually close to the regime of prolonged multiple transmutation in which the minor actinides together with the nuclear fuel are returned to the reactor after a cycle is completed. In the transmutation reactors, the continuous addition of the minor actinides corresponded to the average buildup rate of actinides in a single power-generating reactor VVÉR or SuperPhoenix.

Notice that the SNF from the VVÉR-1000 reactor contains much more ^{237}Np than the SNF from the SuperPhoenix reactor. The nuclide composition of the supplementary charge from VVÉR was 59% of ^{237}Np, 25% of ^{241}Am, and 12% of ^{243}Am, while the nuclide composition of the similar addition from the SuperPhoenix reactor was 9% of ^{237}Np, 75% of ^{241}Am, and 13% of ^{243}Am.

The calculated results on the radiotoxicity of the accumulating actinides in the transmutation reactors in the process of continuous transmutation are depicted in Figs 3 and 4. The data relevant to the radiotoxicity of the actinides accumulating during long-term storage without transmutation are also presented in these two figures.

At the beginning of the transmutation process, the radiotoxicity in the transmutation reactor increases due to the transformation of the long-lived nuclides ^{237}Np, ^{241}Am, and ^{243}Am into the relatively short-lived and more dangerous ^{238}Pu and ^{244}Cm nuclides. In the first 10 – 20 years, the rate of increase of radiotoxicity in all reactors proves to be much higher than in long-term storage without transmutation. Radiotoxicity reaches equilibrium in 20 – 50 years. Its level indicates the radiological hazard present in this or that transmutation reactor. The highest transmutation corresponds to that in fast reactors, although this level is only 1.5 times higher than in the heavy-water CANDU reactor, which has a fairly high neutron flux.

The transmutation process is most effective in the subcritical high-flux accelerator-driven system ELYaU-800. Since this installation uses liquid fuel, a high flux density of thermal neutrons, and continuous disposal of fission fragments, it can operate for a long time in an equilibrium regime with a relatively low level of long-lived radiotoxicity in the blanket.

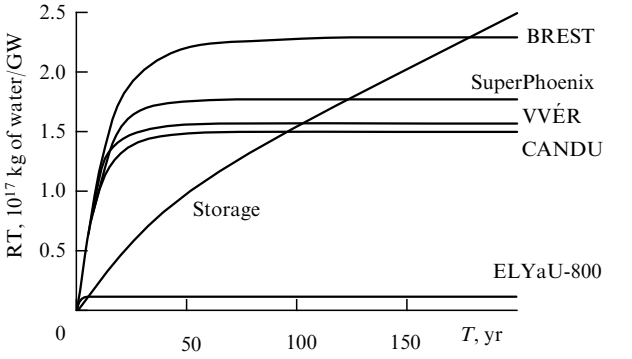

Figure 3. Radiotoxicity (RT) by ingestion in continuous transmutation; actinide make-up from a single VVÉR reactor.

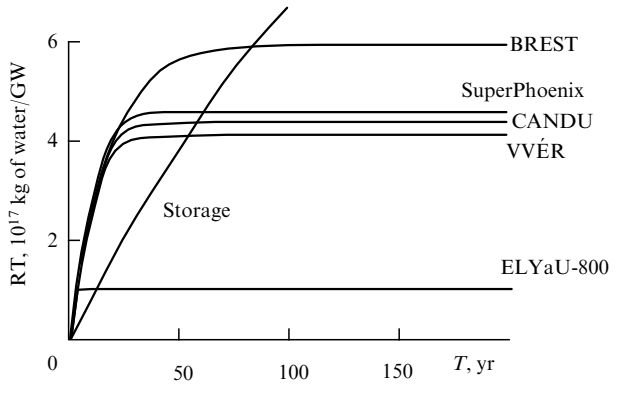

Figure 4. Radiotoxicity (RT) by ingestion in continuous transmutation; actinide make-up from a single SuperPhoenix reactor.

An additional criterion of the transmutation efficiency is the time after which the radiotoxicity of actinides accumulating in transmutation reactors becomes lower than the radiotoxicity of actinides accumulating in a long-term repository without transmutation. For transmutation in nuclear power reactors this time is approximately 100 years. This means that in the first 60 – 120 years simple accumulation of actinides in a specialized storage, from which the actinides cannot escape and pass to the environment, may be considered safer than transmutation. For the high-flux ADS ELYaU-800 this time amounts to 10 years.

This reasoning suggests that if transmutation facilities are designed on the base of ordinary reactors, one type of reactor has practically no advantage over another type.

An effective type of transmutation facilities may be high-flux subcritical accelerator-driven systems using liquid fuel.

8. Use of accelerator-driven systems for actinide transmutation

Actinide transmutation is linked to the specific nuclide composition of the core for units with a thermal neutron spectrum and those with a fast spectrum, where plutonium, americium, and curium constitute a large fraction of nuclides. This leads to two effects influencing radiation safety: the low fraction of delayed neutrons, and positive reactivity effects. In such a situation it is extremely difficult or even impossible to guarantee the nuclear safety of critical nuclear reactors. Hence, for actinide transmutation it is essential to use subcritical systems, i.e., accelerator-driven systems with an accelerator as a source of neutrons (also known as energy amplifiers).

Such systems include a subcritical multiplying blanket (the analog of the core of a nuclear reactor, but with a multiplication factor less than unity), a neutron-producing target irradiated with a proton beam, and a proton accelerator. Owing to the subcriticality of the blanket, accelerator-driven transmutation systems are of higher nuclear safety than critical reactors: in a properly designed accelerator-driven system, no reactivity accidents related to reactor runaway due to prompt neutrons are possible. This makes it possible to avoid the most serious accidents. Note, however, that other types of accidents are still possible, such as in ordinary reactors, e.g., related to a thermal explosion, which may lead to serious consequences for the environment.

Research in accelerator-driven transmutation systems is being conducted in the leading atomic centers all over the world. One of the best-known accelerator-driven systems was developed by a group of scientists led by the Nobel laureate Carlo Rubbia [21].

In Russia, wide-scale research in the field of accelerator-driven systems began in the early 1990s. At the Institute of Theoretical and Experimental Physics (Moscow), blankets were developed for the first studies of such systems that used both solid fuel [22, 23] and liquid fuel with a solution or melt of salts [24, 25, 20]. A detailed account of investigations into accelerator-driven systems in this period can be found in Ref. [26].

The interest in units that use liquid fuel is not accidental — they are best suited for transmutation. In units that employ solid fuel, transmutation is accompanied by multiple fuel

rechargings and chemical processing of the SNF and the actinides undergoing transmutation, which increases the real time of transmutation and the risk of contaminating the environment. Moreover, in such units it is difficult to achieve high neutron flux densities.

Units that are charged with liquid fuel make it possible to continuously reprocess the fuel and the transmutable actinides to easily remove the fission products and add the new actinides, and to maintain a high thermal neutron flux density in the blanket, which means maintaining optimal conditions for actinide transmutation. Calculations and research in design [20] have demonstrated that theoretically it is possible to build a subcritical accelerator-driven transmutation system with the following parameters: a net electric power of 868 MW, an average flux density of thermal neutrons in the blanket of 2×10^{15} neutrons per square centimeter per second, a rate of burning of the minor actinides of 873 kg per annum, and a power consumption of 221 MW for the accelerator. One unit can transmute the minor actinides from 20 VVÉR-1000 power-generating reactors.

9. Conclusions

Radiation safety in the nuclear power industry is closely related to the problem of utilizing radioactive wastes. Since in the future the nuclear power industry will supply a sizable part of our energy, an effective method of destroying radioactive waste must be developed and substantiated. Possibly, transmutation will be needed only in the distant future, when the era of atomic power plants comes to an end. But today the researchers must launch the investigations that will make it possible to demonstrate the real possibility of destroying long-lived radionuclides — society simply will not agree to finance (through taxes) the building of a large number of nuclear power plants without a clear-cut demonstration of the capability to solve the problem of nuclear wastes.

The research that is currently being conducted shows that there is a theoretical possibility of reducing the amount (and risk of radiobiological contamination) of long-lived radioactive wastes through transmutation in nuclear units.

The conceptual study of the different types of transmutation facilities is not finished and must be continued. New systems based on other principles of neutron production that differ from fission reactions may be developed. There are a certain number of unresolved scientific and technical problems needed for the substantiation of the most important parameters and design schemes of accelerator-driven transmutation systems that require further investigation.

References

1. Kolobashkin V M et al. *Radiatsionnye Kharakteristiki Obluchennogo Yadernogo Topliva*. Spravochnik (Radiative Characteristics of Irradiated Nuclear Fuel: Handbook) (Moscow: Energoatomizdat, 1983)
2. *Normy Radiatsionnoĭ Bezopasnosti*: *NRB-99* (Radiation Safety Standards NRB-99) (Moscow: Minzdrav Rossii, Departament Gossanépidnadzora Rossii, 1999)
3. Bergel'son B R et al. *At. Energ.* **89** 215 (2000) [*At. Energy* **89** 729 (2000)]
4. Bergel'son B R et al. *At. Energ.* **90** 31 (2001) [*At. Energy* **90** 35 (2001)]
5. *Strategiya Razvitiya Atomnoĭ Energetiki Rossii v Pervoĭ Polovine XXI veka. Osnovnye Polozheniya* (Strategy of Development of Nuclear Power Engineering in Russia in the First Half of the 21st Century: The Basics) (Moscow: Minatom Rossii, 2000)
6. Murogov V M, Troyanov M F, Shmelev A N *Ispol'zovanie Toriya v Yadernykh Reaktorakh* (Utilization of Thorium in Nuclear Reactors) [Fizika Yadernykh Reaktorov (Physics of Nuclear Reactors), Issue 22] (Moscow: Energoatomizdat, 1983)
7. Salvatores M et al., in *Proc. of the Intern. Conf. on Evaluation of Emerging Nuclear Fuel Cycle Systems*: *Global '95, Versailles, France, Sept. 11–14, 1995* Vol. 1, p. 686
8. Trutnev Yu A, Marshalkin V E, Povyshev V M *Voprosy At. Nauki Tekh. Ser. Teor. Priklad. Fiz.* (3) 31 (1996)
9. Gerasimov A S et al., in *Proc. of the Intern. Conf. and Technology Exposition on Future Nuclear Systems*: *Emerging Fuel Cycles and Waste Disposal Options. Global '93, Sept. 12–17, 1993, Seattle, Washington* Vol. 1 (La Grande Park, IL: American Nuclear Soc., 1993) p. 301
10. Gerasimov A S et al., in *Proc. of the 9th Intern. Conf. on Nuclear Engineering*: *ICONE-9, April 8–12, 2001, Nice, France*, CD-ROM (2001)
11. Baetsle L, Wakabayashi T, Sakurai S, in *Proc. of the Intern. Conf. on Future Nuclear Systems*: *Nuclear Technology — Bridging the Millennia, Global '99, Jackson Hole, WY, USA, Aug. 29–Sept. 3, 1999*, p. 354
12. Gerasimov A S et al. *At. Energ.* **89** 150 (2000) [*At. Energy* **89** 663 (2000)]
13. Bergel'son B R et al. *At. Energ.* **93** 271 (2002) [*At. Energy* **93** 808 (2002)]
14. Rubbia C, in *Technical Committee Meeting on Feasibility and Motivation for Hybrid Concepts for Nuclear Energy Generation and Transmutation, Madrid, Spain, Sept. 17–19, 1997*, IAEA-TC–903.3, p. 33; http://www.iaea.or.at/inis/aws/fnss/fulltext/iaeatc903_3_1.pdf
15. Gerasimov A S et al., Preprint No. 4 (Moscow: Institute of Theoretical and Experimental Physics, 1994)
16. Bergel'son B R, Balyuk S A *At. Energ.* **81** 66 (1996) [*At. Energy* **81** 531 (1996)]
17. Bergel'son B R et al., in *Doklady Konf.* "*Usovershenstvovannye Tyazhelovodnye Reaktory*" (Reports at the Conf. "Advanced Heavy-Water Reactors") (Moscow: ITEF, 1988)
18. Bergelson B R et al. *Nucl. Eng. Int.* **47** (572) 42 (2002)
19. Lopatkin A V et al. *At. Energ.* **89** 308 (2000) [*At. Energy* **89** 827 (2000)]
20. Bergelson B R et al., in *Proc. of the 2nd Intern. Conf. on Accelerator-Driven Transmutation Technologies and Applications, June 3–7, 1996, Kalmar, Sweden* Vol. 1 (Ed. H Condé) (Stockholm: Uppsala Univ., 1997) p. 228
21. Revol J-P *Prog. Nucl. Energy* **32** (1–2) 153 (2001); *Usp. Fiz. Nauk* **173** 747 (2003) [*Phys. Usp.* **46** 725 (2003)]
22. Azhnin E I et al., in *Dokl. II Mezhdunarodnogo Seminara po Transmutatsii Dolgozhivushchikh Radioaktivnykh Otkhodov i Utilizatsii Oruzheĭnogo Plutoniya na Osnove Uskoriteleĭ Protonov* (Reports at the 2nd Intern. Seminar on Transmutation of Long-Lived Radioactive Waste and Utilization of Weapon Plutonium by Accelerator-Driven Systems) Pt. I (Moscow: ITEF, 1994) p. 109
23. Bergelson B R et al., in *Proc. of the 2nd Intern. Conf. on Accelerator-Driven Transmutation Technologies and Applications, June 3–7, 1996, Kalmar, Sweden* Vol. 1 (Ed. H Condé) (Stockholm: Uppsala Univ., 1997) p. 263
24. Blagovolin P P, Kazaritskiĭ V D, Seliverstov V V, Final Report on Project No. 17 of the International Science and Technology Center (Moscow: International Science & Technology Center, 1995)
25. Kochurov B P, Konev B N, in *Dokl. II Mezhdunarodnogo Seminara po Transmutatsii Dolgozhivushchikh Radioaktivnykh Otkhodov i Utilizatsii Oruzheĭnogo Plutoniya na Osnove Uskoriteleĭ Protonov* (Reports at the 2nd Intern. Seminar on Transmutation of Long-Lived Radioactive Waste and Utilization of Weapon Plutonium by Accelerator-Driven Systems) Pt. I (Moscow: ITEF, 1994) p. 56
26. Gerasimov A S, Kiselev G V *Fiz. El. Chast. At. Yadra* **32** 143 (2001) [*Phys. Part. Nucl.* **32** 77 (2001)]