Safety: the key to revitalization of nuclear power

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About a decade ago, when the future construction of nuclear power plants was a topic of wide discussion at the I. V. Kurchatov Institute of Atomic Energy, three different assumptions about the pace of development were made: rapid, medium, and slow (the average prediction was for up to 150 GW(e) total power from nuclear plants). It can now be stated that the rate of development has turned out to be slower than the lowest predictions. Even the term "development" must be put in quotation marks. And it is not only the fact that Russia is undergoing a profound economic reform and reorganization of industry, for the decline of nuclear began earlier. The cause was the reaction of society to the Chernobyl accident.

According to some estimates heard recently, the total damage from the Chernobyl accident came to around 300 billion rubles.* Regardless of how much money the damage is expressed as in our rapidly changing economic life, this sum is comparable to the total profit from nuclear power over its entire existence. When we add to this the weight of anti-war propaganda against nuclear weapons, which in many respects is timely and warranted, it becomes clear that the defenders of nuclear power face a very unfavorable psychological climate.

The discovery of nuclear energy is the highest achievement of science, and it cannot be covered up and forgotten. We must learn to use it not to do harm, but for the good of humanity. Whereas chemical energy involves the rearrangement of the outer electron shells of atoms, nuclear reactions transform the nuclear material, neutrons and protons, which are bound together in the nucleus by forces millions of times stronger than those between the electrons in the atom. It is for this reason that a power production of 1 GW(e) can be sustained at a nuclear power plant by consuming 1 tonne (1000 kg) of uranium per year, while the same output from ordinary thermal power plants requires millions of tonnes of organic fuel (the abbreviation GW(e) stands for the electrical power, which is about one-third of the total power released).

One hardly needs to belabor the advantages of nuclear energy from an ecological standpoint: not only has much been written about this, it is obvious in itself, since the production of nuclear energy involves the external environment in a minimal way during normal operation of a nuclear power plant. It is necessary only to give an unbiased assessment of the role of nuclear energy in the overall scheme of energy production and, in particular, to refute some common stereotypical ideas:

1. The extraction of uranium from the earth and, conversely, the storage of radioactive fission products will upset the global radioactive balance. This is undoubtedly true, but nuclear energy is not alone in this respect.

Every human interference in the natural processes upsets the balance of nature. And does nature really sustain less damage when we civilized people attempt to consume in one hundred years all that nature has accumulated over many millions of years in the form of petroleum, coal, and natural gas? In the form of forests and grasslands, in the form of clean water in lakes, rivers, and seas? Since some degree of interference is unavoidable, we must reach an agreement as to what is possible and what is unacceptable given all that man is not yet willing to give up in his daily life: travel to any point on the planet by airplane, which pollutes the atmosphere, by ship, which pollutes the sea; heat in his home, television, telephone, electric irons and all such devices, which all require energy sources damaging to nature, which have led to the drying up of the Aral Sea and the black water of the Volga River, with bream floating belly-up and sturgeon being dashed on the rock piles of the Volga Hydroelectric Plant.

Compromise is always complicated. Even such a goal as, for example, "the longest average human life span," cannot be considered ecologically sound, since what seems favorable today may turn out to be just the opposite to our grandchildren one hundred years hence.

2. Another incorrect idea, at least in its absolute expression, is that nuclear energy does not come from God but is contrary to nature, that man and all living things have developed without protective instincts against radioactivity.

First of all, there are also many harmful chemical substances that do not carry warning signs: carbon monoxide is colorless and odorless, while the strongest poison, potassium cyanide, has only a slight scent of bitter almond, and so forth.

Secondly, our whole life it actually permeated with radiation from the Earth and from space. The natural background can change by a factor of 2 or 3 owing to circadian, seasonal, and solar variations. Certain populated regions, such as the southwestern part of India and the Atlantic coast of Brazil, have a radioactive background that is 10 times the average on account of monazite sands containing radioactive thorium. Besides the natural background, which is a more or less constant component, there are individual variations that depend on the specific build-

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ing one lives in or on medical treatments one is taking; this component is on average 2.5 times higher than the background and cannot be regarded as fixed. In other words, we live with radiation, our organism has been adapted to it, and, as some scientists believe, radiation is the source of the genetic mutations that, loosely speaking, underlie the development of all living things.

3. People speak of nuclear power in strong language. Nuclear power plants are sometimes called "time bombs." Many people think that Chernobyl has proven that nuclear energy is an unsound concept. All attention has been focused on the danger of nuclear energy while events in other regions, no less tragic than Chernobyl, have been pushed to the back page; however, the comparison is illuminating.

In 1984 there were two major accidents. In Mexico there was an explosion in a tank of liquified natural gas at a gas-distributing plant near Mexico City. There were 452 persons killed, 1000 missing, and 4248 injured. Buildings were destroyed in a 1-km radius. The blast was similar to the explosion of a small atomic bomb.

The second accident occurred in Bhopal, India, where a deadly gas, methyl isocyanate, was released. There were 2,500 dead, hundreds of thousands made ill, and the damage was estimated at 50 billion dollars.

Any complex production process involves risk. Since one cannot picture a developed society without fuel and chemicals, accidents, as an unavoidable evil, are the price we must pay. The situation with nuclear energy is less obvious: it is far from universally believed that nuclear energy is needed at all.

On the other hand it is known that countries such as Japan and especially France have surpassed Russia many times over in the development of a nuclear energy base. It would be naive to assume that this development is a rash step on their part. The point is that those countries, which lack sufficient fuel resources, became convinced earlier than others that nuclear energy is environmentally clean (in normal operation, of course) and economically appropriate. Incidentally, it is sometimes pointed out that nuclear facilities pose a particular hazard in times of war. Indeed, the destruction of a nuclear plant (like other large industrial facilities) could make the already terrible aftereffects of war many times worse. As a quantitative estimate of the hazard of nuclear energy in the event of any war, whether nuclear or conventional, one can take the total nuclear power capacity per unit area of the landmass. This gives a valid estimate if the number of nuclear power plants is sufficiently large, since the length of the deadly radioactive plume from the destruction of a plant extends for hundreds of kilometers, and at a width of tens of kilometers these plumes will overlap each other. In terms of this parameter Russia (the European part) trails the USA (excluding Alaska) by one-and-one-half times and Western Europe by many times.

The purpose of the preceding discussions was not somehow to depreciate the radioactive hazards of nuclear energy. It was meant to emphasize the important fact that nuclear energy does not pose the unique danger to people that is now ascribed to it.

It has long been noted by researchers that the standard of living is proportional to the amount of energy produced by a society. Russia's lag behind the advanced countries of Europe, the USA, and Japan is expressed primarily in the energy "saturation" of our industry and home life (lower by about half) and in the rational, economical expenditure of energy (another factor of 1.5).

The fact that we need to save energy, as well as other material resources, is incontrovertible Energy conservation, while an economical investment of capital, is nevertheless not free. It involves the assimilation of new technologies, improved machinery, thermal insulation of buildings, etc., i.e., it takes time to implement and is a secondary process that is accessible to a society that has attained a certain technical level.

In the search for alternative approaches to organic and nuclear energy sources, the one that is mentioned most often is solar energy (which, by the way, is also nuclear).

The exploitation of natural energy sources runs up against the main shortcoming of such sources: they are diffuse and unconcentrated. The pretty pictures showing modern windmills should not lead us astray: with a blade diameter of 10 m and an average wind speed of 10 m/s (36 km/h), such a windmill can produce only a few kilowatts of electric power, and in order to compare with a 1 GW power plant there would have to be about a hundred thousand of them. At middle latitudes the solar energy flux is about 150 W/m^2. It is easy to calculate that a 1 GW(e) solar electric plant would require an area of about 100 km^2 completely covered with photocells. Besides using an enormous amount of materials, including some in extremely short supply, it is still not clear whether we would achieve a reasonable net gain of energy,i.e., whether the solar energy produced would be greater than the energy expended on its extraction. It is also uncertain that such an energy source would be as environmentally benign as is widely claimed. The problem lies not only in the manufacturing waste products and the dispossession of large amounts of land. Imagine that, as in the case of a good nuclear plant, the one-third portion of the solar energy of such a plant in the form of electricity is carried on transmission lines from the southern to the northern regions of the country. But this means that in terms of the amount of heat that can be obtained from the sun, Dushanbe, for example, would be comparable to Petrozavodsk. The large-scale use of solar energy runs up against environmental difficulties just as great as those facing the construction of a hydroelectric plant.

Thus, our primary thesis is that it will be possible to achieve a high level of energy production in a comparatively short time (10 years) only through the universal adoption of nuclear energy. This position has a number of points in its favor.

Whether we like it now or not, the industrial development in the USSR was, for many reasons, predominantly of a military nature: nuclear, rocketry and space, aviation, and several others. Enormous intellectual efforts and material resources were spent on the development of the corresponding scientific research institutes, design and construction offices, test facilities, etc. The equipment and experimental facilities at the plants of the former Ministry of Medium Machine Building were substantially better than the average level in the country, and the qualifications of the scientific and engineering staffs were up to world standards. It would be wasteful, unreasonable, and even absurd for our society not to take advantage of the high level of production at these plants. Money ought to be spent not where we are weak and backward, but where we are strong and competitive in the world.

It is now clear that the world has started on the road to extensive nuclear disarmament. This will soon free up an enormous amount of nuclear materials: around 100 tonnes of Pu-239 and 1000 tonnes of U-235. This amount of fissionable materials is sufficient for 40 years of operation of the nuclear power plants now in service. For the more economical and promising reactors of the future, which will be discussed below, it would be enough to last many centuries.

Would it be reasonable, especially in our impoverished state, not to use this "free" nuclear fuel? The tens of billions of rubles spent on the creation of military technology would be returned to peaceful uses: in nuclear power plants the cost of the fuel component reaches 15–20% of the cost of production of electrical energy. Finally, is it really better to begin to construct storage depots for military-grade plutonium and uranium and to post the large number of guards that would be necessary, which would be economically ruinous, or, worse still, as some "hot heads" have proposed, to dispose of these valuable materials, more costly than gold, by burying them in the ground?

However, regardless of whatever words and incantations are pronounced, society will not accept nuclear energy if it is not completely convinced of its safety. Nor will it help to cite the examples of Japan and France; after all, things are different over there.

Circumstances have changed dramatically since the first nuclear power plants were constructed. Before, the most important thing was to economize on fissionable materials and their turnover, and so the reactor core was stressed to the limit in terms of energy release. Today the situation is different: there is a surplus of uranium, both because of disarmament and also because of the sharp decline of the nuclear energy program.

The priorities are now completely different: safety is paramount.

A safe reactor, in the terminology I prefer, is one that will not in any uncontrollable situation create radioactive contamination outside the reactor hall. An inherently safe reactor is a safe reactor in which an accident is put down not through the efforts of a human operator but automatically, by physical effects built into it.

Let us recall some facts.

The reactions occurring in a nuclear power plant involve the fission of heavy (uranic and transuranic) elements, while those in thermonuclear reactors involve the fusion (synthesis) of the lightest elements, at present exclusively isotopes of hydrogen (deuterium and tritium).

The fission reaction goes through means of neutrons and can be brought about at any temperature, including room temperature, and that lends an enormous advantage to nuclear power plants, while the thermonuclear reaction requires an "unearthly" temperature of 100 million degrees.

In each fission event a number ν of neutrons are formed; for $\nu > 1$ a branched chain reaction can occur, since the neutrons of the previous generation can create the neutrons of the next generation. Depending on the composition and mass (size) of the material, the neutron chain can either grow (an explosive supercritical situation) or die out (a subcritical system). In the reactors of nuclear power plants a steady-state energy release is maintained, i.e., a critical state intermediate between supercritical and subcritical. Sometimes the concept of a neutron multiplication coefficient K is introduced: K is the number by which one must divide ν in order to convert a supercritical ($K > 1$) or subcritical ($K < 1$) state into the critical state.

The odd isotopes of uranium and plutonium (U-233, U-235, Pu-239, Pu-241) can be fissioned by neutrons of any energy, while the even isotopes (U-238, Pu-240) have an energy threshold and are weakly fissioned by neutrons in the fission spectrum and are not fissioned at all if the neutrons are slowed. Only the odd isotopes can form a critical mass. A reactor core is, as a rule, constructed from a mixture of even and odd isotopes of uranium, with a U-235 content of a few percent. In such a combination, the U-238, even while not fissioning, has a beneficial effect. On capturing a neutron, U-238 is converted to U-239, which then, after two β decays in 2.5 days is converted to the very fissionable Pu-239. Thus the spend atoms (U-235) are replaced by other atoms (Pu-239). An important characteristic of any reactor, the breeding ratio (B.R.), gives the ratio of the number of active atoms created to the number consumed. In thermal neutron reactors B.R. ≈ 0.5, and essentially only U-235 is burned. In fast neutron reactors B.R. > 1, and in such reactors not only is energy released but there is an increase in number (multiplication) of the fissionable atoms. In other words, through plutonium, U-238 is also drawn into the fission process. This circumstance is of fundamental importance.

One of the arguments made by the opponents of nuclear power plants is that the intensive development of nuclear energy will exhaust its fuel resource in the form of U-235 by the year 2010 or 2020. While this is true today, i.e., in reference to the type of nuclear power plants now in service, it completely loses validity if fast breeder reactors are included. Not only is the abundance of U-238 in nature 140 times greater than that of U-235, but it would also become economically profitable to recover uranium from "low-grade" ores, which are much more plentiful, and even to extract uranium for granite and sea water. Therefore, the resource base is expanded practically without limit.

Two types of critical state are distinguished: the lower critical state, which includes all the neutrons in the balance, and the upper, which excludes the so-called delayed neutrons. A fission event produces not only prompt neutrons (the overwhelming majority) but also additional neutrons in the course of a minute or so (around 1.5%). If the lower critical state is crossed but the upper is not reached, the rate of development of the chain reactions is restrained by the time required for the delayed neutrons to appear, and there is sufficient time for actuation of a mechanical safety system (the introduction of neutron-absorbing rods into the reactor core). The transition through the upper critical state is inadmissible or very dangerous, since the growth of the neutron flux occurs over a characteristic time of only a fraction of a millisecond.

The questions of reactor safety are not limited to the transition through the upper critical state and the development of an explosive process. Radioactivity can be released in other kinds of accidents as well. For example, a failure (rupture) of the cooling system can have very serious consequences. Even in a shut-down reactor there is residual heat release due to the radioactive decay of the accumulated reaction products. This residual heat release can be great enough to melt the core, causing a release of radioactivity to the environment.

However, it must be kept in mind that the rate of residual energy release per unit volume of the fuel element is proportional to the working power of the reactor per unit volume. By lowering the specific power one can decrease the residual energy release to a level at which the heat is removed naturally and will not melt the fuel element. By increasing the fuel burnup (efficiency), one can achieve the very important goal of attaining a lifetime of the fuel element in the reactor that matches the service life of the nuclear power plant, i.e., 50–100 years. This is also an important factor for improving the safety and simplifying the operation of the plant.

The search for reactor designs in which everything is subordinate to an overriding idea, safety, has absolute priority, even at the expense of some other economic and technological imperatives.

One final question that pertains to the safety of nuclear power plants and their environmental acceptability for society is that of arranging a closed cycle of radioactivity.

It would be inadmissible in a program of large-scale production of nuclear energy to have a large accumulation of radioactive materials that would contaminate the land. Some ideas on this topic are discussed in the last part of this review.

Three requirements must be fulfilled as a necessary condition for safety of a nuclear reactor: it must not admit an unsanctioned transition through the upper critical state, nor a loss of containment of the fuel elements (or of the reactor as a whole) in the event of a complete failure of the cooling system, nor a buildup of radioactive materials in environmentally hazardous quantities.

In the existing VVÉR and RBMK reactors there are undoubtedly significant possibilities for improvement from a safety standpoint. However, that is not the purpose of this article. It is important to emphasize a different point: reactor physics has much more to offer than has been demanded of it. The cardinal rule of safety must be followed: the working state of the reactor must be a preferred, best-organized (lowest entropy) state, every deviation from which will cause the reaction to die down and stop the release of heat.

The sphere, the geometric figure with highest degree of perfection, has the lowest ratio of surface area to volume and consequently has the lowest critical mass: any disruption of the shape will take it from the critical state to a subcritical state.

The construction of the pulsed fast reactor is well known: it has a stationary part and a moving part. When they are brought together for a short time a slight supercriticality arises and a chain reaction develops proportionately.

Now let us imagine that there is not one, not two, but, say, one hundred such uranium disks, all rotating at frequencies that are multiples of some frequency: 1 Hz, 2 Hz, and so on up to 100 Hz. Then one time in every 100 s they will come together and form a slightly (1%) supercritical system in the form of a cylinder, so that there is a pulsed energy release. Any disruption of the synchronization even in one of the disks would render the device subcritical. In spite of the schematic nature of this example, it contains still another useful suggestion. Most of the time the disks are found in a separated state, with a highly developed surface. One can take advantage of this for cooling them (by radiational, air, water, or other cooling method). It is an extremely favorable situation from the standpoint of the neutron balance and the burnup of fuel, since the heat release and heat removal are separated in time and space. During the times of "burning" the core contains a minimum of the extraneous moderating and absorbing materials, and during the heat removal one can use the most convenient materials for that purpose.

Three more proposals are made below: examples of a fast, a thermal, and a hybrid (fission–fusion) reactor, all possessing inherent safety.

The goal is not to give a precise technical description of the reactor design but rather to convince the reader that nuclear energy can be brought to a high level of safety and has a right to exist and deserves priority in development.

Fast reactor. In a fast reactor there must not be any noticeable amount of light elements capable of effectively moderating the neutrons (in particular, water must not be used as a coolant).

A fast reactor is inferior to a thermal reactor in all respects (capital expense, ease of operation) except one: that for the sake of which it was conceived. As we have said, in a fast reactor the breeding ratio B.R. > 1, and such a reactor can serve as a breeder of fissionable atoms, which can be used for fuel in other reactors.

Among all their differences, fast reactors and thermal reactors have one thing in common: both of them consume (burn up) the active component of the fuel (U-235, Pu-239) in the core. In other words, the original store of active material in these reactors is greater than is required for immediate maintenance of the critical level. Therefore, the system is balanced by control rods: neutron absorbers. As the fuel is used up, the rods are withdrawn, so that the reactor is maintained in a steady state. Since the fuel elements in any reactor have a finite service life in the core, they initially contain a certain margin of supercriticality, which is larger the longer the proposed life cycle. In this sense, none of the currently existing reactors, which work on the burnup principle, can be classified as unconditionally safe, and if the control rods are suddenly removed from the core as a result of some accident, a significant supercriticality will arise. Under such conditions the chain reaction will develop uncontrollably rapidly, since a transition through the upper critical state will have occurred.

On the subject of fast reactors we have made two statements that would seem to be mutually exclusive. At the beginning we said that fast reactors are breeders, and later we said that they, like thermal reactors, are designed around depletion of the core. Do they accumulate fuel or burn it up?

Both statements are correct. This can be understood if it is recalled that a fast reactor is divided into two zones: a central zone with a high concentration of the active material, where the fission reaction occurs, and a peripheral zone consisting of U-238, where the plutonium is accumulated. The breeding ratio for the core of the reactor alone is actually less than unity, while the breeding ratio for the reactor as a whole, i.e., with allowance for the plutonium that has been produced in the breeding zone, is greater than unity. After removal from the reactor, the fuel elements of both zones will be reprocessed at chemical plants. The separated plutonium and uranium will again be placed in the reactor.

Isn't this a strange picture? After going around the cycle, the plutonium, five years later, has returned to its starting point, in the same (or a neighboring) reactor. Why? It would really be much simpler and better to burn it in place and save the time spent in transportation and reprocessing.

Furthermore, what if the two zones of the fast reactor were replaced by a single zone in which the two were mixed in such a proportion as to provide both criticality and the breeding function? The disadvantage of such a mixing is obvious: the critical mass of the reactor would increase sharply, tending to infinity for a mixture of uranium with $\sim 4.5\%$ plutonium. (The consumption of plutonium required to maintain criticality increases from kilograms to tonnes when the plutonium concentration is changed from 100% to 5%.) Nevertheless, this shortcoming can hardly be considered significant, since a nuclear power plant burns up around a tonne of fissionable material a year (per 1 GW(e)), and many times more is stockpiled.

One can demonstrate this possibility without doing a long calculation. One starts from a single fact: a fast reactor can have a breeding factor greater than unity, and this has been demonstrated experimentally. It is easy to show that the breeding factor can be expressed in the form

$$\text{B.R.} \approx \frac{\tilde{P}}{P_c} U_8;$$

here $U_8 \approx 1 - P_c$ is the concentration of U-238 in a mixture containing the critical concentration of plutonium P_c, and $\tilde{P}$ is the so-called equilibrium concentration of plutonium,

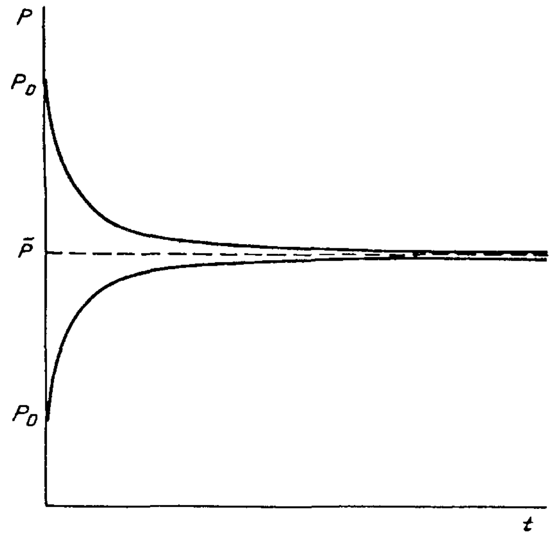

FIG. 1. Plutonium concentration as a function of time. The upper curve corresponds to burnup of plutonium, the lower to accumulation. P_0 is the initial concentration of plutonium. The equilibrium concentration $\tilde{P}$ is equal to 10% for a fast reactor and 0.25% for a thermal reactor.

to which the concentration tends during burning, independently of whether it was initially larger or smaller than $\tilde{P}$. It is only for initial concentrations $P_0 > \tilde{P}$ (the core of the fast reactor) that depletion occurs ($\tilde{P}$ is approached from above), while for $P_0 < \tilde{P}$ there is accumulation (the equilibrium concentration is approached from below, as in the breeding zone) (see Fig. 1).

So what happens if we make a single-zone reactor in which $P_c < \tilde{P}$ (B.R. > 1)? The answer is that, left to itself, such a system cannot pass through the critical state, in spite of the fact that the plutonium concentration tends to the value $\tilde{P} > P_c$. What is the explanation for this seemingly paradoxical situation?

In the description of the development of the neutron chains and the kinetics of conversion of some elements into others, there are two relevant times. A neutron produced in a fission event disappears after a mean lifetime $t_n \sim 10^{-6}$–10^{-7} s. The plutonium atom that has fissioned is replaced by a new one (after the neutron is absorbed by a U-238 atom) after a time $t_{1/2} \approx 2.5$ days, i.e., after a delay dictated by the β-decay time. The two time parameters t_n and $t_{1/2}$ have greatly different scales, and the course of events is always determined by the longer time. If the reactor stays in its working state for years, the delay in the appearance of the plutonium, expressed in days, is not important. The situation is entirely different if something causes the system to suddenly go supercritical. The extra plutonium caused by the supercriticality disappears with a time t_n, and the system returns to its former (critical) state. The additional neutrons do cause additional plutonium to appear, but only after several days and over an extended period of time.

In the chain of disappearance and appearance of the plutonium a new time, $t_{1/2}$, has come in, which is reminis-

TABLE I. Free burning of a reactor with plutonium accumulation, when left to itself.

Breeding ratio, B.R.	Burning time, days	Burnup of U-238, %
1	970	20
1,3	250	40
1,5	50	60
1,7	30	70
1,9	20	77

For a neutron lifetime $t_n \approx 10^{-6}$ s and a β-decay time $t_{1/2} \approx 2.5$ days ($n + U-238 \xrightarrow{\beta} Np-239 \xrightarrow{\beta} Pu-239$) the burning time is dictated by the long β-decay time with a large numerical dimensionless coefficient.

cent of the minute delay for the delayed neutrons, during which time the system cannot attain the upper critical state. Since the accumulation of plutonium happens "from below," the characteristic time for an increase in power reaches many days; this introduces a most important element of safety.

The circumstance that $P \to \tilde{P}$ but cannot become greater than P_c means that the critical state is maintained automatically. In other words,there is no need for regulation by control rods and the intervention of an operator. If such a reactor is left to itself, there will first be a growth in the power (in the neutron flux) and then, together with the burnup of U-238, a dying down. One might say that in such an autonomous reactor an "explosion" develops which lasts many days (for B.R. ≈ 1.5 the burning time is about $10t_{1/2}$, i.e., about a month). The reaction comes to an end, since $\tilde{P}$ is proportional to the concentration of U-238, and sooner or later the breeding ratio will become less than unity ($P_c > \tilde{P}$). But this occurs after a very significant burnup of fuel, on the scale of 50%. The deep burnup of fuel is yet another advantage of the proposed reactor. Table I gives some data for this autonomous evolution.

However, the rate of energy release and the variability of the power of this reactor may be technically unacceptable. A standard reactor consumes about 1% of its fuel in a year, while our reactor would consume tens of percent per month. This is a result of the excessively fast accumulation of plutonium. This rapid production can be suppressed by dilution as well as by burning.

Suppose that when a certain power level is reached one begins to change out some material, adding inert U-238 to the core and removing some of the old, plutonium-containing material. A high rate of replacement would decrease the average concentration of plutonium, and the reaction would die down. Consequently, there exists a rate of replacement of the fuel elements at which one can stabilize the power of the heat release at an arbitrary level. Moreover, at a certain safety factor (B.R.$\geqslant 1.5$) it turns out to be possible to reach a steady state in which fresh uranium fuel elements are put into the reactor and old fuel elements containing fission fragments and residues of uranium and plutonium are removed at a uniform rate over time. It can be shown that if the rate of replacement of the fuel elements is chosen such that the time of service of a fuel element in the reactor is substantially longer than $t_{1/2}$, then the rate of energy release will be determined by the rate of replacement. This way of regulating the reactor should not be equated with the existing system of reactor control, since it is not performing a protective function. It could be entrusted to a computer, since any errors will not result in an accident but will only cause the power of the reactor to fluctuate (and this could be corrected by a very simple feedback). We note that if instead of pure U-238 one puts in U-238 with plutonium that has been extracted from the old fuel elements, i.e., with only the fragments removed, the steady state will be easier to achieve, becoming possible at B.R.$\geqslant 1$.

A simple geometric picture of this "steady-state" reactor can be constructed as follows. Suppose we have an infinite cylinder of uranium about 1 m in diameter. In some part of it we mix in plutonium so as to create a critical volume. A chain reaction begins. Part of the neutrons escape through the ends of this volume and are absorbed by the uranium. At a sufficiently high energy release the plutonium concentration in the adjacent regions will become larger than the critical value, and then the center of energy release will move along the cylinder. A traveling neutron-fission wave will arise. Under certain conditions (B.R. > 1.5) the initial conditions will gradually be forgotten, and a steady-state burning wave will form, with a velocity that follows from dimensional considerations:

$$D \approx \frac{L}{t_{1/2}} \text{ (mm/day)}$$

where L is the range of the neutron in the material. This wave travels into the fresh uranium, leaving the burned material behind it, and the analogy with the steady-state reactor is obvious. The dependence of the velocity on $P_c/\tilde{P}$ is shown in Fig. 2.

The "propagation" factor can be adopted for efficient and economical use of military-grade, highly enriched U-235 and Pu-239 recovered in the build-down of the nuclear arsenal.

A primary critical mass is created in concentrated material (where it is a small amount–tens of kilograms instead of tonnes) surrounded by inert U-238. The amount and geometry of the active material are chosen such that the neutrons of the core which are captured in the U-238 breed plutonium in an amount sufficient to maintain a critical state. Gradually the whole reactor will be enveloped by the burn and be "powered up."

In concluding this section we should point out the following fact. In the proposed reactor, as we have said, a deep burnup of the fuel occurs, and it is not designed to supply plutonium to other reactors. For this reason the fuel does not need to be chemically regenerated (open cycle) or, if it is reprocessed, only a partial processing is done to separate the heavy and light (fragment) fractions to meet the needs of this reactor alone.

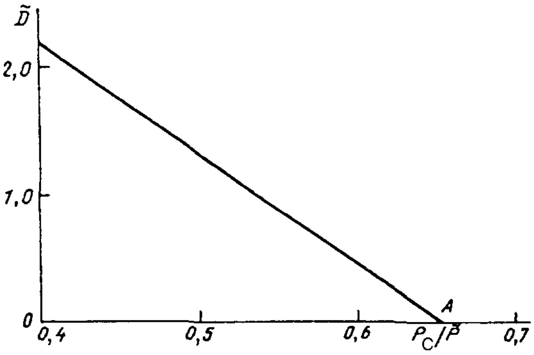

FIG. 2. Velocity of a steady-state burning wave in U-238. $\tilde{D}$ is a dimensionless quantity defined by the relation: $D=\tilde{D}L/t_{1/2}$, where D is the velocity of the wave and L is the neutron absorption length in the medium ($L \approx 5$ cm). Notice the point A at which the velocity goes to zero (after which there is no steady-state solution). This means that by appropriately choosing the critical concentration P_c(which depends on the size of the critical system and the neutron spectrum) and the equilibrium concentration $\tilde{P}$ (which depends only on the spectrum), one can achieve a velocity that is acceptable in terms of heat removal. Similarly, for a reactor with continuous refueling (for $P_c/\tilde{P} \gtrsim 0.64$, i.e., for B.R. $\approx \tilde{P}/P_c \approx 1.5$) a steady state in which the power is dictated by the rate of refueling can be attained.

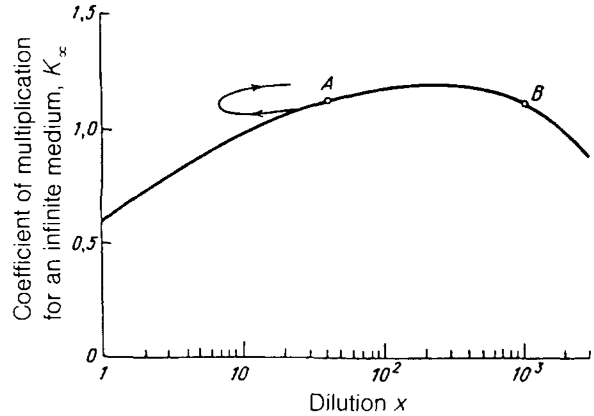

FIG. 3. Point A (unlike point B) is stable: a small increase in the power (evaporation) shifts the working point to the left and makes the system slightly subcritical. The arrow indicates the change in the dilution of the core of the reactor in the course of prolonged burning (years).

In 1980, President Carter of the USA made a decision to stop the development of the fast breeder reactor. This decision was reached for reasons of safety. In order for breeder reactors to fulfill their function and begin to supply fuel to other reactors, including thermal nuclear power plants, a mighty network of chemical plants would be needed to extract plutonium from the spent fuel. An enormous amount of plutonium, comparable to the amount prepared in a decade for military purposes, would circulate every year among the facilities of the nuclear industry. This raises the threat of uncontrolled dissemination of plutonium and with it, nuclear weapons. This problem would not exist for the fast reactor considered here.

Thermal reactor. As we have said, the best nuclear cycle is realized in fast-neutron reactors. The use of thermal reactors may be justified by their simplicity and familiarity. Of all the known types of thermal reactors, the best neutron balance is found in a heavy-water reactor of the Canadian "Candu" type, which uses natural (unenriched) uranium as fuel. Figure 3 shows a plot of the multiplication coefficient K_∞ for an infinite medium as a function of the uranium concentration $x = N_{D_2O}/N_O$. It is seen from Fig. 3 that values $K_\infty > 1$, for which, in principle, a steady-state reactor can exist, correspond to dilutions in the range $10 < x < 1000$. The rolloff on the right-hand side of the curve is due to the weak, but finite absorption of neutrons in the heavy water. The rolloff on the left, for small x, is due to a change in the neutron spectrum: the spectrum becomes harder and enters the region of resonance absorption in U-238. It is this branch of the rolloff that we will be interested in below, for it is associated with the idea of physical regulation (as opposed to the forced regulation by control rods in a standard reactor).

Let us assume that the reactor was started up at a point with a concentration on the left-hand branch, $10 < x < 100$. Burning begins, and with it comes a change of the fuel components: U-235 gradually disappears, and Pu-239 and fragments accumulate. The most important thing is that the breeding properties of the core initially become stronger in a heavy-water reactor, rather than declining as usual on account of the burnup of U-235. In other words, B.R.$\geqslant 1$. However, the growth in activity soon stops, since the equilibrium concentration of plutonium in the case of thermal neutrons, $\tilde{P} \approx 0.25\%$, does not compensate the burnup of the 0.7% U-235 contained in the natural uranium. This is why the burnup in the Candu reactor is low, at the level of the original U-235 content in natural uranium.

Figure 4 shows a diagram of the proposed reactor. A distinctive feature of this reactor is a closed volume containing an open water surface, with the heat transfer inside the reactor by free convection of water vapor and with the

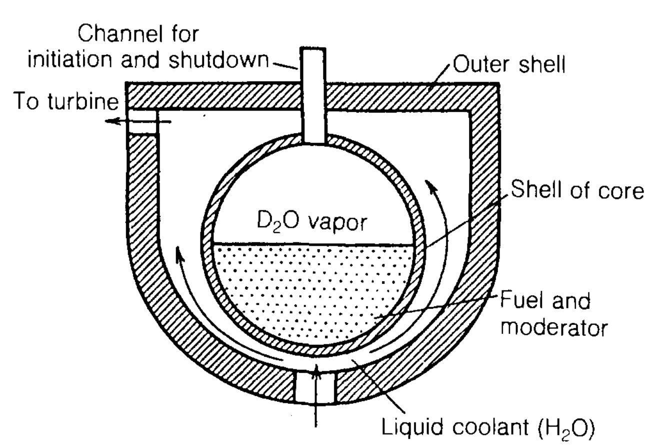

FIG. 4. Diagram of a reactor with an evaporating core. The dots in the core indicate the points at which the thin horizontal uranium fuel elements intersect the plane of the diagram. Heat removal can be accomplished (for a developed surface) by means of pipes entering the upper part of the core (the inner sphere). The shape (not necessarily spherical) and composition of the core are optimized.

TABLE II. Some data on the calculational characteristics of a reactor.

Power	30 MW
Radius of core chamber	$R=3$ m
Load	20 tonnes natural uranium, 50 tonnes heavy water
Vapor pressure in chamber	~100 atm
Burnup of uranium during the service life of a fuel element in the reactor	Around 2%

coolant outside the core. Initially, owing to the growth in activity and the more intense evaporation of water, the concentration of active atoms increases and there are changes in the neutron spectrum and escape. As the dilution x decreases and resonances come into effect, the equilibrium concentration of the plutonium shifts to higher values, and the accumulation of plutonium continues. After a certain time the burning will involve almost exclusively plutonium (from U-238), and this increases the burnup by several times (the economy in terms of natural uranium is four times better than for the VVÉR reactor) (see Table II).

The most important quality of the proposed design is the self-regulating character of the operation and the consequent absence of any control system. The functioning of this reactor possesses the same property of safety based on physical principles of which we spoke earlier. Whatever the cause, an accidental increase in the heat release will cause additional evaporation of the moderator and the reaction will rapidly be curtailed on account of the increasing hardness of the neutron spectrum and the escape of neutrons. A very good feature of this reactor is the separateness of the zones of energy release and energy removal. This makes it possible to use ordinary water in the first cooling circuit. The proposed reactor has two other remarkable features. The rate of heat removal regulates the heat release (power). In fact, increasing the power of heat removal causes cooling of the reactor and more intense condensation of the heavy-water vapor, and thus leads to greater energy release.

Let us now consider the most serious kind of accident: a complete interruption of the heat removal. This is nothing to worry about. The accident will develop very slowly, requiring tens of minutes for the water to completely evaporate. And actually it will take much longer, since pretty soon the chain reaction will be broken off because of the growth of the uranium concentration in the heavy water. The elevated vapor pressure can be let off through a one-way valve into an auxiliary tank, once and for all.

All the advantages mentioned, however, come at the expense of a strong reduction in the heat removal per unit volume, and so the reactor will have to be correspondingly larger and more massive. This is the main shortcoming of this reactor. But, as they say, every cloud has a silver lining. The reactor will hold all the fuel (natural uranium) it needs to run without refueling for its entire 50-year lifetime. In addition, the residual specific heat release, which is proportional to the specific power of the reactor, will be lowered to such a degree that the fuel elements will not melt even in the absence of water.

Fission–fusion (hybrid) reactor (this section of the article was prepared for publication by a group of authors led by N. G. Basov). The third type of reactor is obviously safe by its very nature. This is a subcritical reactor in which the energy release is maintained in a steady state by means of an external source of neutrons. This external neutron source could be a particle accelerator exciting nuclear reactions or a thermonuclear fusion reaction in isotopes of hydrogen. Another possibility that should be mentioned is a fast reactor placed inside a thermal reactor, which can be treated two ways: as a reactor with a single but inhomogeneous core, or as a thermal reactor whose energy release is maintained by a central fast reactor having a power some tens of times less than the total power.

A reactor combining a fission part and a fusion part is commonly called a hybrid reactor. The discussion below is confined to this type of reactor.

Ordinarily a hybrid reactor, which contains a passive surrounding blanket of U-238, is considered as a breeder of plutonium for nuclear power plants. In that case the term blanket is essentially the same as the breeding zone of a fast reactor, and carries the same logical absurdity: Why produce plutonium in one place so that, after paying for the transport and reprocessing, you can use it years later somewhere else?

However, it is immediately clear that the combined system of a subcritical assembly and a thermonuclear source of neutrons is noticeably more complex than either one taken by itself. Therefore, one must be completely clear in answering the question as to what are the advantages of such a combination.

We have already spoken about safety against explosion. This is ensured by the subcriticality of the core. In such a reactor the control system, as ordinarily conceived, is simplified or absent altogether. The rate of energy release is dictated completely by the power of the thermonuclear source: turning it off will quickly stop the fission.

Finally, the presence of an external source, the doping of the neutrons, improves the neutron balance and leads to a higher burnup of the uranium. For example, according to calculates, at a multiplication coefficient $K=0.95$ (meaning that each external neutron will give rise to $1/(1/\text{-}K)$ $=20$ fission neutrons, or ten fissions) the degree of burnup in a heavy-water reactor using natural uranium will reach 3.5–4%, i.e., the economy in terms of the amount of natural uranium spent is almost 10 times better than in the VVÉR and RBMK reactors.

Of all the thermonuclear and accelerator sources of neutrons, the clear preference is for a periodically pulsed source based on laser fusion. The reasons for this preference include, among others, that it is only for laser fusion that the thermonuclear burning zone (the target chamber) is separate from the energy supply (the lasers themselves) by tens of meters. The burning chamber itself, with the channels for the laser radiation (it is best to have just one channel, i.e., to use one-sided illumination), is compact

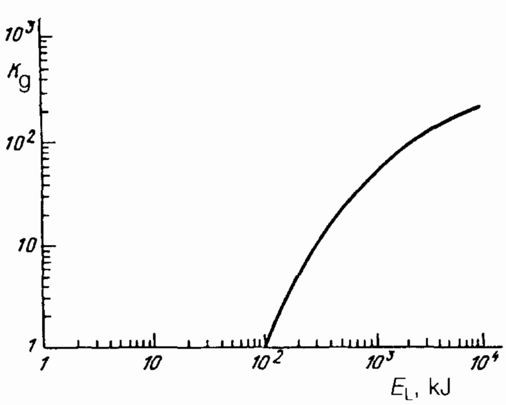

FIG. 5. Gain $K_g$of a thermonuclear target (the ratio of the thermonuclear energy to the energy in the laser beam) versus the laser energy. For a purely fusion reactor the working region is found at an energy of several MJ, while for a hybrid reactor it is at 100–200 kJ.

and can quite easily be placed in the core of the reactor. It would be practically impossible to do this with a tokamak or accelerator.

But if one is going to build the necessary laser and excite the thermonuclear reaction, then why have the uranium and the fission? Wouldn't it be simpler to have just the fusion energy alone? How "clean"! And that's how they're trying to do it in the advanced countries of the USA and Japan!

The word "clean" is in quotation marks for a reason. The reactor of a nuclear power plant contains an enormous amount of radioactivity, and, even if reduced by a factor of 100, ti would still be enormous. Thermonuclear reactions produce high-energy neutrons which, even if there is no uranium surrounding them, interact with all the structural materials, being above threshold in several different channels: (n,2n), (n,p), (n,α). These reactions give rise to a so-called induced radioactivity which is essentially no different from that of fission fragments. By suitably choosing the materials one can avoid long-lived radioactivity, and this is the main advantage of fusion over fission as a means of energy production, since in fission the nature of the radioactivity is dictated by the nature of the phenomenon itself and cannot be regulated. Any nuclear method of energy production will entail to some degree the problem of radioactivity and will always pos a large radioactive hazard in case of an accident.

It is commonly assumed that, with allowance for the efficiency of the laser, the energy chain for a fusion power plant can be closed (one can obtain a positive energy balance) if the thermonuclear gain, which is the ratio of the nuclear energy released to the laser energy, is of the order of 100. From the curve of the gain various laser energy in Fig. 5 we see that $K \approx 100$ is reached at laser energy of several MJ. Such a laser, capable of firing once per second or so for a period of ten years, would cost an estimated 1 billion dollars or more.

Let us now return to the hybrid scheme. Let the degree of subcriticality of the uranium blanket be such that each neutron produced by the fusion reaction will result in ten fission events. Since each fission event releases 10 times more energy than the fusion reaction, the preponderance of the energy release will come from fission and only about 1% from fusion. Requiring as before that the total gain $K = 100$, we see that the gain for the laser fusion part could have a value $K_{fus} \sim 1$. From the curve of Fig. 5 we see that the energy requirements for the laser at $K_{fus} \sim 1$ are tens of times lower,just 100–200 kJ, which are achievable today in a single-shot mode. The cost of the laser is lower in about the same proportion, and such a laser becomes feasible from the standpoint of both cost and service life.

In the hybrid scheme the main energy is from fission, and while the laser complicates the construction, it does lend such a reactor a high degree of safety, simplicity of control, and high fuel burnup and economy. With all these advantages, the hybrid reactor is fully deserving of the status of a separate class of device. Only time will tell if the hybrid reactor will be a completely independent entity or only a step, perhaps a detour, on the path to mastery of fusion energy. We believe that for "poor" Russia this course is the only one, being in equal measure useful for the development of both fission and fusion energy.

Radioactivity. In this section we will be discussing not accidents involving the uncontrolled release of radioactivity but rather the normal technological production of nuclear energy in electrical power plants and the accompanying output of radioactive products.

Let us start with some numbers pointing up the seriousness of the problem. A single nuclear power plant (with an output of 1 GW(e)) produces 1 tonne of fragments a year, more than all the radioactive fragments produced in underground testing of nuclear weapons in the entire history of the Semipalatinsk Polygon. And what if there is not just one but twenty or even a hundred such plants?

The Hanford Nuclear Reservation in the northwestern USA, like our Chelyabinsk "Lighthouse" (Mayak), was created for the production of plutonium for military purposes. The extraction of plutonium is accompanied by the discharge of a large amount of radioactive waste water into rivers and lakes. According to the estimates of American scientists, the recultivation of the land, i.e., its restoration to normal agricultural activity, would cost at least 100 billion dollars. What would happen if instead of the 50–100 tonnes of military plutonium produced in 40 years, there was close to this amount of plutonium coming from fast reactors every few years? Won't great ecological calamities await us and future generations if we embark today on a program for the large-scale development of nuclear energy?

In answer to this and other such questions, one could cite the examples of France and Japan and ask, "How can we, with our wide open spaces, with our industrial legacy from the former Ministry of Medium Machine Building, and with our rich experience, be afraid?"

But I will nevertheless hazard a more concrete answer and attempt to sketch out an acceptable path, to give an understanding of where the "bottleneck," the crux of the problem, lies. All radioactive products associated with uranium and fission can be divided into two groups: the tran-

TABLE III.

Transuranic isotope	Half-life t_α for decay with the emission of an α particle, years	Half-life t_{sf} with respect to the spontaneous fission channel, years
U-238	$4,5\cdot 10^9$	$8,0\cdot 10^{15}$
Pu-239	$2,4\cdot 10^4$	$5,5\cdot 10^{15}$
Pu-240	6580	$1,2\cdot 10^{11}$
Pu-241	14,5	—
Pu-242	$3,9\cdot 10^5$	$6,8\cdot 10^{10}$
Pu-243 $\xrightarrow{\beta(5h)}$	$8\cdot 10^3$	
Am-243		
Am-244 $\xrightarrow{\beta(10h)}$		—
Cm-244	17,6	$1,4\cdot 10^7$
Cm-245	$8,5\cdot 10^3$	—
Cm-246	$5,5\cdot 10^3$	$1,7\cdot 10^7$
Cm-247	$1,5\cdot 10^7$	—

suranic elements, which arise as a result of the capture of neutrons by uranium, and uranium daughter products and fission fragments. The first of these are characterized by extremely long half-lives: thousands and even millions of years (although there are exceptions). The second, in contrast, usually live for only a short time, from seconds to several years or decades.

In what follows we will proceed from the fact that through chemical manipulations the heavy uranium and transuranic elements can be separated from the fragments and, as necessary, individual elements or groups of elements can be isolated from the fragments.

The problem, both environmental and economic, is to ensure that the stored materials (mainly fragments) contain only a small amount (at the level of parts per thousand) of heavy elements, such as plutonium, with long half-lives, for they are what will determine the environmental situation after thousands of years.

The cost and feasibility of such technology must be weighed against the cost of the environmental measures required for the operation of power plants burning organic fuels, each of which [with a capacity of 1 GW(e)] puts millions of tonnes of ash into the atmosphere.

Table III lists the set of elements arising as a result of uranium–plutonium conversions. An increase in fluence, i.e., the integral of the neutron flux over time, is accompanied by a change in the composition and a shift toward heavier isotopes. The chain is broken off at curium-247, since the subsequent isotopes decay rapidly and do not affect the composition. Each of the isotopes has a dual fate: it is created from the preceding isotope and vanishes either through decay and fission or by trapping a neutron and creating the next isotope. Therefore, after a sufficiently long time the concentrations of all the isotopes will take on their steady-state values.

The breeding properties of the mixture are characterized by the parameter

$$D=\sum_i [(\nu_i-1)\sigma_{fi}-\sigma_{ai}]C_i,$$

where the summation is over all components C_i of the mixture (σ_f is the fission cross section and σ_a is the cross section for neutron absorption).

It becomes clear that, in terms of its nuclear-physical parameters the steady-state mixture, i.e., the limit in time, is just as good as the initial mixture, and so can be used over and over again. This presents a radical way of eliminating radioactive transuranic elements: they can be burned in the same reactors in which they are created. In itself, this fact is not surprising. The transuranics, supersaturated with neutrons, have an enhanced tendency to fission. For example, it is known that for Cm-245 the critical mass is several times smaller than for Pu-239. Meanwhile, it must be said that in spite of the fundamental clarity of the situation, significant technical difficulties may be encountered. A quick calculation shows that in the steady-state mixture (without uranium) the heat release is hundreds of times, and the neutron background tens of thousands of times, larger than in standard plutonium. In addition, the degree of residual radioactive contamination depends directly on the thoroughness of the chemical processing, on how completely the dangerous elements have been separated out.

Fragments. Fragments can be divided into 3 groups, according to their lifetimes. We shall assume that a nuclear power plant exists for 50 years. By the end of its life, most of the fragments, having lifetimes of a few years or less, will have decayed in the storage pits at the site.

However, there is a group of fragments that have very long decay half-lives, 10^6–10^7 years or more. These fragments are only slightly radioactive and do not present an environmental danger, since they can add little to the natural radioactivity of the Earth.

Thus it is the fragments with mean half-lives of 5 years to a million years that should be separated out. Their characterizations are given in Table IV.

The majority of these isotopes do not present a real hazard. If the energy of the β-decay electrons is less than 100 keV, then a protective iron coating 1 mm thick will absorb practically all the radiation—the electrons and the accompanying bremsstrahlung. The weak penetrating radiation is a favorable circumstance for the creation of isotope radiation sources.

Three isotopes require special attention: Kr-85, Cs-137, and Sr-90. Kr-85, an inert gas, enters the atmosphere and causes additional ionization and conductivity in it. After several tens of years its content in the atmosphere reaches equilibrium, which is such that the ionizing radiation from its decay is $W=2\cdot 10^4 M$ W [M is the power of all the nuclear power plants, expressed in GW(e)]. In its effect on the atmosphere this would compare with cosmic radiation, which on entering the atmosphere has a value $1.4\cdot 10^9$ W. For $M=10^3$ the correction to the cosmic component is noticeable but not large: 1–2%. The situation

TABLE IV.

Element	Half-life t (β)	Yield, % [kg/year · GW(e)]	Decay energy, MeV	Energy of γ rays accompanying decay, MeV
Kr-85	11	0,13(0,44)	0,67	—
Sr-90	28	2,2(7,9)	0,55	—
Zr-93	$1,5\cdot10^6$	4(14,9)	0,06	—
Tc-99	$2,1\cdot10^5$	6,1(24)	0,29	—
Pd-107	$7,0\cdot10^6$	1,4(6,0)	0,04	—
Cs-135	$3,0\cdot10^6$	7,2(39)	0,21	—
Cs-137	30	6,5(36)	0,17	0,66
Sm-151	87	1(6)	0,08	0,02

requires attention but is not yet alarming, since the concentration of ions above dry land and the sea varies by a factor of six or more.

Strontium-90 is created during fission together with the stable isotope Sr-88 (the remaining isotopes decay rapidly). The neutron absorption cross section of Sr-88 is smaller by a factor of approximately 200 than for Sr-90, so that it is possible, after separating the strontium chemically and returning it to the reactor, to burn up the dangerous component. In addition, Sr-90 does not emit nuclear γ rays and is therefore used as an isotope radiation source.

A completely different situation exists in regard to Cs-137, which is most harmful and is mainly responsible for the post-Chernobyl situation today. Cs-137 is created during fission in equal amounts with the stable Cs-133, but it has a cross section for ($n\gamma$) reaction that is smaller by a factor of 300. Therefore, if the cesium is placed in a reactor, the destruction of Cs-137 will be far less than the production of Cs-134 ($t_{1/2}=2.05$ years, β,γ). Perhaps someone will think of some other reactions (nuclear transmutations) with high-energy neutrons, but for now it must be assumed that long-term (1000 years) storage will be necessary. Although this would not be simple, it would be doable, since the amount in question is small, about 100 kg per GE(e).

Conclusion

1. The economic development of society requires extensive generation of electrical energy.

Nuclear energy must be assigned the leading role in fulfilling this function, since organic feedstocks are expensive and are being exhausted, while nuclear fuel is a practically unlimited resource. The existing stocks in the form of enriched uranium and plutonium, which are needed for nuclear power plants, are sufficient to last for many years. The established structure of the nuclear facilities of the atomic industry, the availability of qualified workers and scientists, and the need for conversion from military to peaceful enterprise are all favorable for this, and the economic advantages are practically irrefutable.

2. In this article we have demonstrated some purely physical means by which a steady-state energy release can be maintained automatically in a reactor, so that its safety is not subject to human error. The concepts presented are not designs, even schematic ones, for reactors, but only some ideas intended to confirm that the possibilities encompassed by the essential physics of a reactor are far from exhausted.

3. Analysis of the data on the radioactivity accompanying fission holds out the hope that the problem of arranging a closed production in which the radioactive materials stay in the proximity of the plant may also prove to be manageable, partially through chemical reprocessing of the fuel and repeated burning in the reactor, and partially through storage of a small amount of selected material. Thus there is no reason that should stand in the way of a large-scale adoption of nuclear energy.

There has been talk to the effect that Japan, which is constructing nuclear power plants in a resort area, is not a suitable example for "peasant Russia." May those words remain on the conscience of those who have done nothing intelligent in either industry or science.

In addition to the references cited below, this article has made use of extensive computational work done recently by V. Ya. Gol'din's group at the Center for Mathematical Modeling of the Russian Academy of Sciences, which was published as Preprint No. 43 in 1992. I would like to thank all my colleagues who worked on this article, and I. L. Tsvetkova for editing and proofreading the manuscript.

*Translator's note: the term "billion" is used throughout this paper to mean 10^9, or 1 milliard.

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