The twenty-first century as the century of nuclear power*

V. I. Subbotin
Russian Academy of Sciences, Moscow

Fiz. Élem. Chastits At. Yadra **29**, 333–388 (March–April 1998)

The current status of the present and future energy sources available to mankind is reviewed. Fundamentally new directions in the future development of nuclear power based on the fission of heavy nuclei are proposed. It appears realistic to build a new generation of nuclear power plants which are free from the current defects, produce minimal radioactive waste, and use up almost all the natural uranium or thorium fuel. © *1998 American Institute of Physics.* [S1063-7796(98)00202-2]

Here the spirit must be strong–Here fear must not suppress discussion.
Dante

Energy sources play a crucial role in modern society. In order to have a high standard of living, a country must have a sufficient number of diverse sources of energy for generating electricity, for manufacturing and farming, for ground, air, and sea transportation, and for heating and daily life in general.

Many developing countries do not have sufficient energy sources of their own, and are forced to purchase energy on the world market. The demand for hydrocarbon fuel is constantly growing throughout the world. Some countries purchase natural uranium and nuclear fuel to supply their nuclear power plants. A country with inadequate energy supplies and without the means to buy them is doomed to poverty.

Land and air transportation strongly influence the standard of living in modern societies. It is possible to travel to another continent in less than a day. Traveling a distance of hundreds of kilometers in a day is not a problem.

Oil is of special importance, as it is the energy source for transportation. In principle, the use of other sources of energy can lessen the demand for petroleum. For example, in some cases electric power can replace petroleum as an energy source, directly by replacing liquid fuel as in the electrification of railroads, or indirectly by producing materials for energy storage as in the production of hydrogen from water. The production of an energy carrier requires an initial expenditure of energy with an efficiency of less than unity.

Great selfishness will arise if in several decades modern man exhausts all the available supplies of petroleum and natural gas. We must not just talk, we must act to ensure that in the not-so-distant future mankind will have sufficient supplies of petroleum and natural gas, which are unique natural sources of energy satisfying most of the requirements of everyday life at the end of the twentieth century.

Obviously, when determining the supplies of petroleum and natural gas it is not sufficient to consider these supplies up to the point at which they are completely gone. It is necessary to keep a reserve sufficient for a reasonable number of years, the time it would take to fundamentally reorient ourselves regarding energy sources. If we extract oil from the earth until the supply is exhausted, we will end up with a catastrophe much worse than any ecological disaster.

Useful fossil fuels available in amounts sufficient for thousands of years at the highest rate of use, such as natural uranium and thorium in the lithosphere, have important advantages over useful fossil fuels such as petroleum and natural gas, which occur in amounts sufficient for decades. Errors in predicting supplies are critical in the latter case. Errors of prediction in the first case by even orders of magnitude are not so important, because the energy reserves in nuclear fuel are enormous.

The end of the twentieth century has witnessed serious efforts to promote ecology and the legislated protection of nature. Our culture of extraction, transport, and exploitation of energy sources is a fundamental component in the protection of nature. The present environmental safeguards are very expensive. The closer we approach exhaustion of our petroleum supplies, the more acute become the priorities for using these supplies. Owing to imperfect methods of extraction, drilling for the oil remaining in the older petroleum-producing regions of the earth is technologically complicated and not always economically feasible.

In the very near future it will become extremely important to cut back on the use of valuable hydrocarbon fuels in electric power generation and to implement a rigorous energy-conservation policy. It will be necessary to transform electric power generation to nuclear power generation with a closed fuel cycle maximally safe in all its aspects and to ecologically clean electric power generation based on coal.

The resources which must be expended for large-scale nuclear power generation are quite comparable to those which must be expended in exhausting petroleum reserves and changing over to other energy sources, especially for transportation. The only difference is that in the former case the money must be available to spend today and petroleum will be reserved for top-priority needs, while in the latter case the money will be needed in 20–30 years and petroleum will become rare.

The transition from petroleum products to energy-accumulating materials will affect most energy consumers, and large-scale nuclear power generation will still be required to obtain such materials.

Owing to nuclear explosions and the accidents that have occurred at nuclear power plants and radiochemical plants, people fear and mistrust nuclear power. However, they will be forced to rely on it as much as possible for energy production in the future when maximally safe nuclear power plants are built. There are no other sources of energy which are as concentrated in nature. The energy contained in nuclear fuel can supply mankind's requirements for thousands of years.

In spite of all the complications of the present time, it is important to deal carefully with the problem of ensuring energy sources in the future. Russia possesses unique reserves of hydrocarbon fuel, but they are also approaching exhaustion.

Electric power plants producing electrical power and heat currently use the following energy supplies:

(a) Hydrocarbon fuels such as coal, natural gas, and petroleum residue (mazut).

(b) Hydropower.

(c) Atomic energy.

Nuclear energy should become the main source in the twenty-first century, even though this has not happened by the end of the twentieth century for several reasons, among them: the availability of sufficient amounts of oil and natural gas on the world market at affordable prices, accidents at nuclear power plants causing distrust in society, and the lack of convincing ideas for ensuring nuclear and radiation safety.

Owing to the simplicity of the physics of burning, obtaining thermal energy by burning hydrocarbon fuel in heat engines will always be less expensive than using nuclear and thermonuclear reactors which transform nuclear energy into heat. The most serious accidents that have occurred at thermal power stations cannot be compared to the possible consequences of even a moderately severe accident at a nuclear power plant. Present-day nuclear power generation leaves a radioactive legacy. On the other hand, nuclear power generation does not require oxygen from the atmosphere and does not contribute to the greenhouse effect.

The burning of hydrocarbons in steam boilers, automobiles, and airplanes increases the concentration of greenhouse gases, especially carbon dioxide, in the atmosphere. A local decrease of atmospheric oxygen can occur in poorly ventilated areas. Dust, SO_2, NO_x, and incompletely burned hydrocarbons are emitted into the atmosphere. Keeping the emissions of these materials within safe limits for humans and nature greatly increases the cost of hydrocarbon-based electric power generation. It is impossible to use hydrocarbons without any environmental safeguards. Containment of the carbon dioxide is unrealistic, owing to the scale at which it is produced.

The increased costs of hydrocarbon energy sources and of their extraction and transport and the expense of environmental safeguards may make safe nuclear power generation more ecologically appealing than the use of hydrocarbons. Already now in some regions of the world it is economically advantageous to use nuclear energy.

Is nuclear energy necessary? Can it be made safe? Today these questions are asked by professionals directly or indirectly concerned with energy reserves, power generation, ecology, and economics. These are also the questions asked by consumers of electricity, heat, and motor fuel, and who receive sensational information from the press, television, and radio.

Mankind living in the late twentieth century has a variety of energy sources. Some of them are common and familiar, like oil, natural gas, coal, and water power. Others, such as energy from the fission of heavy nuclei, are exploited to an already significant degree. Solar energy, used directly, plays its role. Strictly speaking, organic fuel is an accumulation of solar energy from earlier geological epochs. The fusion of light nuclei is a source still in the research stage. There is no inescapable need to have a single source of energy.

The beginning of the twentieth century was characterized by the global use of petroleum. Petroleum is the best of all the energy sources known to mankind. It is easier to extract from the earth than other energy sources. It is easy to transport over any distance using tankers or pipelines. It can be transported at normal temperatures and low pressures.

A new energy source appeared in the middle of the twentieth century: natural gas. Natural gas is easily extracted from the earth. It can be transported at high pressure over large distances via pipelines. Natural gas is the ecologically cleanest hydrocarbon fuel. The final products of normal burning are water vapor and carbon dioxide. Natural gas is widely used in daily life, in city boilers and in thermoelectric power stations inside large cities.

The lifetime of a gas pipeline is 25–30 years, after which it must be replaced by a new one. The relative efficiency of CO_2 in generating the greenhouse effect is 1, and for natural gas it is 27. Losses of natural gas during extraction, transport via pipeline, and use at the destination contribute to the greenhouse effect, just like the combustion products. Large amounts of natural gas are emitted into the atmosphere in accidents at pipelines and gas-pumping stations.

Coal, the reserves of which considerably exceed those of oil and natural gas, has again become foremost among hydrocarbon energy sources. When it is mined, coal must be as free as possible from the rock accompanying it in order for it to be transportable over large distances. This is also necessary for ecological reasons. Rock contains natural radioactive isotopes. If a large amount of dust is contained in the smoke from burning coal, it is practically impossible to remove it.

The emissions into the environment of radioactive products from a modern, normally operating nuclear power plant are smaller than those from a normally operating thermoelectric plant of the same power output which burns coal containing a large amount of rock.

THE STRUCTURE OF WORLD ENERGY RESERVES

Coal

Known deposits: $(0.476–0.59)\times 10^{12}$ tons.

Available thermal energy: $(9.5–11.8)\times 10^{21}$ J.

Possible deposits: $(3.2–7.6)\times 10^{12}$ tons.

Possible thermal energy from these deposits: $(6.4–15.2)\times 10^{22}$ J.

Oil

Known deposits: $(90-100)\times 10^9$ tons.

Available thermal energy: $(3.4-3.8)\times 10^{21}$ J.

Possible deposits: $(200-350)\times 10^9$ tons.

Possible thermal energy from these deposits: $(7.6-13.3)\times 10^{21}$ J.

Natural gas

Known deposits: $(52-78)\times 10^{12}$ m^3.

Available thermal energy: $(2.0-3.0)\times 10^{21}$ J.

Possible deposits: 330×10^{12} m^3.

Possible thermal energy from these deposits: 12.8×10^{21} J.

Uranium

Known deposits: $(1.75-2.36)\times 10^6$ tons.

Available thermal energy:

(a) In thermal neutron reactors burning 1% natural uranium: $(1.4-1.9)\times 10^{21}$ J.

(b) In breeder reactors with closed fuel cycle burning 60% natural uranium: $(8.4-11.4)\times 10^{22}$ J.

The complete combustion of 1 kg of carbon gives 3.37×10^7 J of heat.

The complete combustion of 1 kg of high-quality coal gives 2.9×10^7 J of heat.

The complete combustion of 1 kg of natural gas consisting of methane (CH_4) gives 5.0×10^7 J of heat.

One m^3 of natural gas gives 2.77×10^7 J of heat.

The complete combustion of 1 kg of carbon requires 2.67 kg of oxygen. This produces 3.67 kg of carbon dioxide (CO_2). The complete combustion of 1 kg of methane consisting of 0.75 kg of carbon and 0.25 kg of hydrogen requires 2 kg of oxygen for burning the carbon and 2 kg of oxygen for burning the hydrogen. This results in the production of 2.75 kg of CO_2 and 2.25 kg of water. The burning of carbon in the atmosphere to produce 10^6 J gives off 0.109 kg of CO_2. The burning of methane gives off 0.056 kg of CO_2.

NO_x is produced from atmospheric nitrogen in combustion. SO_2 is produced when hydrocarbon fuel containing sulfur is used. The combustion products CO_2, SO_2, and NO_x are emitted into the atmosphere. SO_2 and NO_x are transported over large distances by air masses, and fall as acid rain causing acidification of soil and the water of reservoirs and rivers, which leads to the death of flora and fauna.

France is now the ecologically cleanest industrially developed country, owing to the very widespread use of atomic energy. Roughly 75% of the electric power in France is produced by nuclear power plants. The CO_2 emission per person per year is 1.7 tons. In Germany, where nuclear power supplies about 30% of the energy needs, 3.0 tons of CO_2 are emitted per person per year. In the United States, where about 21% of the electricity is supplied by nuclear power and where there is a great deal of automobile transport, the CO_2 release is 5.0 tons per person per year.

The greenhouse effect in the Earth's atmosphere—the ability of the atmosphere, due to the presence of CO_2 and water vapor, to allow ultraviolet radiation from the Sun to pass through while trapping infrared radiation—is an integral feature of the Earth. Increased CO_2 emissions and the loss of methane during the extraction, transport, and burning of natural gas can upset the thermal balance of the Earth. A rise of the Earth's temperature increases the amount of water vapor. An increased water-vapor content in the atmosphere enhances the greenhouse effect.

There is a great deal of political and scientific speculation about the greenhouse effect throughout the world. The fluctuations in the Earth's climate do not give a unique indication of the actual influence of the greenhouse effect generated by human activity.

As science and technology have developed, mankind has learned to use new energy sources which have large potential energy per unit mass. More complicated technology has been required to liberate this energy.

The twentieth century has given mankind energy from fission and fusion. The problem of the energy crisis has been solved in principle. The thoughtless expenditure of energy is inadmissible. Efforts at energy conservation are being made in developed countries. Significant results have been obtained. Russia still has a long way to go in this direction. Energy conservation can correct energy consumption. It can make it rational and efficient, but it cannot make sources of energy unnecessary.

Conventional fuel

1 kg of conventional fuel=7000 kcal=2.926×10^7 J.

Coal

4000–7000 kcal/kg=$(1.67-2.926)\times 10^7$ J/kg.

Crude petroleum

9100 kcal/kg=3.8×10^7 J/kg.

Natural gas

$t=20$ °C; $P=1$ atm; $\rho=1.3$ kg/m^3;

1 m$^3\to$9300 kcal=3.89×10^7 J.

Methane

$t=20$ °C; $P=1$ atm; $\rho=0.554$ kg/m^3;

1 m$^3\to 2.77\times 10^7$ J.

1 kg (1.8 m^3)$\to 5.0\times 10^7$ J.

Gaseous hydrogen

$t=0$ °C; $P=1$ atm; $\rho=0.0899$ kg/m^3;

1 m$^3\to 1.1\times 10^7$ J.

1 kg (11.12 m^3)$\to 1.2\times 10^8$ J.

Fission of heavy nuclei

Fission energy per nucleus $\approx$200 MeV (3.2×10^{-11} J).

Fission energy per kg$\approx 8\times 10^{13}$ J.

Fusion of light nuclei

(D+T) fusion energy=17.59 MeV (2.8×10^{-12} J).

1 kg of the mixture (0.4 kg D+0.6 kg T)=3.36×10^{14} J.

(D+D) fusion energy=14.43 MeV (2.3×10^{-12} J).

1 kg D$\to 3.46\times 10^{14}$ J.

GLOBAL ESTIMATES OF NUCLEAR ENERGY

Mass of the Earth's core $\approx 2.8\times 10^{22}$ kg.

Mass of the hydrosphere $\approx 1.37\times 10^{21}$ kg.

FISSION ENERGY

Content of natural uranium: 99.2745% ${}^{238}_{92}$U, 0.720% ${}^{235}_{92}$U, 0.0055% ${}^{234}_{92}$U.

In the Earth's core: $(2.5\times 10^{-4}-3.0\times 10^{-4})$ percent by weight $\approx 7.0\times 10^{16}$ kg; uranium-235$\approx 4.9\times 10^{14}$ kg; in sea water=3.4×10^{-8} percent by weight of uranium.

The uranium content in the Earth's mantle is not taken into account, owing to its inaccessibility in view of foreseeable technology.

THORIUM CONTENT

Naturally occurring thorium $^{232}_{90}Th$—100%.

In the Earth's core $\approx 1.3\times 10^{-3}$ percent by weight or $\approx 36\times 10^{16}$ kg.

In the complete fission of only uranium-235 (without uranium-238, plutonium, and direct fission of uranium-238), an amount $\approx 4.9\times 10^{14}$ kg will give $\approx 3.9\times 10^{29}$ J. In the complete fission of all naturally occurring uranium this is $\approx 0.56\times 10^{31}$ J. In the complete fission of thorium this is $\approx 2.88\times 10^{31}$ J. The maximum energy in the complete fission of naturally occurring uranium and thorium is $\approx 3.44\times 10^{31}$ J.

FUSION ENERGY

Let us consider the type of fusion which is most likely to be realized in the foreseeable future.

1. The fusion of ^2_1D obtained from heavy water, a component of naturally occurring water, and ^3_1T obtained from nuclear reactions involving the naturally occurring isotope ^6_3Li.

At energies above 1 keV (11.6×10^6 K),

$$^2_1D+^3_1T\rightarrow ^4_2He+^1_0n+(17.59\text{ MeV or }2.8\times 10^{-12}\text{ J}).$$

About 80% of the energy is carried off by neutrons: 14.07 MeV.

About 20% of the energy is carried off by α particles: 3.52 MeV.

In one kg of the mixture $^2_1D+^3_1T$, i.e., 0.4 kg ^2_1D and 0.6 kg $^3_1T\rightarrow 1.2\times 10^{26}$ pairs of nuclei; 1 kg of the mixture can give 3.36×10^{14} J.

2. Fusion at higher energies above 10 keV (116×10^6 K) can be realized using only ^2_1D:

$$^2_1D+^2_1D\rightarrow ^3_1T+^1_1H,$$

$$^2_1D+^3_1T\rightarrow ^4_2He+^1_0n,$$

$$^2_1D+^2_1D\rightarrow ^3_2He+^1_0n,$$

$$^2_1D+^3_2He\rightarrow ^4_2He+^1_1H.$$

About 38.2% of the energy is carried off by 14.07 and 2.45 MeV neutrons.

About 40.9% of the energy is carried off by 14.67 and 3.0 MeV protons.

About 16.6% of the energy is carried off by 3.52 and 3.68 MeV α particles.

The two ^2_1D nuclei together release 14.41 MeV (2.3×10^{-12} J).

In 1 kg of ^2_1D there are 1.5×10^{26} pairs of nuclei; 1 kg of ^2_1D can give 3.46×10^{14} J.

The water of the world's oceans contains $\approx 4.57\times 10^{16}$ kg of deuterium.

Naturally occurring lithium consists of 92.58% ^7_3Li and 7.42% ^6_3Li.

The Earth's core contains 3.2×10^{-3} percent by weight of naturally occurring lithium or $\approx 8.96\times 10^{17}$ kg, including $\approx 6.65\times 10^{16}$ kg of ^6_3Li and $\approx 8.29\times 10^{17}$ kg of ^7_3Li.

The burning of 6.65×10^{16} kg of ^6_3Li requires $\approx 2.22\times 10^{16}$ kg of ^2_1D. A mixture of 8.87×10^{16} kg can release 2.39×10^{31} J.

In principle, it is possible to burn only deuterium of the hydrosphere in an amount $\approx 4.57\times 10^{16}$ kg. In this case 1.58×10^{31} J will be released.

A radiant energy of 6.6×10^{24} J/yr reaches the Earth from the Sun. About 20% of this, i.e., 1.32×10^{24} J/yr of solar energy, is absorbed by the Earth, giving rise to a water evaporation–condensation cycle and mass transfer in the atmosphere and the hydrosphere, along with photosynthesis in the ocean and on land. Estimates of the thermal contamination of the environment by humans do not exceed 10^{22} J/yr, i.e., about 1% of the absorbed radiant energy.

The planet Earth has existed for about 4.6×10^9 yr. Complete burning of only the uranium-235 of the Earth's core, assuming that there are no other energy sources, that would take $\approx 3.9\times 10^7$ yr.

The complete burning of all the naturally occurring uranium, assuming that there are no other energy sources, would take $\approx 5.6\times 10^8$ yr. For thorium this number is 2.88×10^9 yr.

The complete burning of lithium-6 and part of the deuterium of the hydrosphere would take 2.39×10^9 yr.

The complete burning of all the deuterium of the hydrosphere would take $\approx 1.58\times 10^9$ yr.

In harnessing the energy produced by the fission of heavy nuclei, mankind has acquired an unlimited source of energy. Moreover, mankind also has a second unlimited source of energy: the energy of the fusion of light nuclei.

It is simplest to obtain thermal energy by burning natural gas. The most difficult way to obtain it is by the controlled fusion of light nuclei. Natural gas cannot provide a source of energy for a long period of time. The use of natural gas for power production can give us breathing space while we develop maximally safe nuclear power generation based on the fission of heavy nuclei, and later based on the fusion of light nuclei.

Economic estimates of power production obviously must somehow take into account the scientific potential which a country acquires when it has mastered significantly more complicated technologies. A high scientific potential is an achievement of a nation. At the present time it is not taken into account in economics. What would happen if we halt the scientific search for maximally safe nuclear power generation and mastery of fusion, and also close all the nuclear power plants? Would we rely on natural gas for all our energy needs?

Scientists—emigrants from Europe, scientists from the United States, Britain, France, and the Soviet Union—have laid the scientific foundations for the release and control of nuclear and thermonuclear energy. If the mastery of nuclear energy had not extended beyond the mastery of destructive weapons, even by now we would not have had controllable nuclear energy at our disposal. The countries possessing nuclear weapons have spent enormous amounts of money to create these weapons, and, of course, this money would not have been made available by the governments of those countries for any peaceful projects.

In the United States and the Soviet Union, huge scientific and engineering groups were created and led by a broad front of theoretical, experimental, technical, and engineering researchers focused on the creation of nuclear and thermonuclear weapons. Mankind had no previous experience in forming and managing such large groups of people designed to solve a single problem. Most of the research carried out was completely new.

The path into the unknown produced results. In December 1942, Fermi succeeded in achieving, for the first time ever in the world, a self-sustaining nuclear reaction and then stopping it. The first plutonium bomb was exploded in 1945 in the United States.

Ideas about the use of energy produced in the fission of actinide nuclei for power production first developed in the late 1940s in the United States and the Soviet Union. The first such power generators were developed for nuclear submarines.

Light-water-cooled graphite channel converters for obtaining bomb-grade plutonium served as the basis for designing the first atomic power plant in the world and the RBMK reactors.

Pressurized light-water reactor vessel, first used in nuclear submarines, served as the basis for modern energy-generating pressurized water reactors.

Isotope-separation plants for extracting weapons-grade uranium-235 from naturally occurring uranium served as the basis for obtaining the enriched fuel used by modern power reactors.

The radiochemical processing for extracting artificial plutonium from irradiated slugs discharged from converters served as the basis for the modern processing of irradiated fuel from power reactors.

Already in the 1950s the completely new industry of nuclear-fuel production was operating at full capacity in the United States and the USSR, and a large amount of fissile material was produced. It became possible to use a part of it not for nuclear weapons, but for power generation.

The development of nuclear weapons, and then nuclear power generation for a very different purpose, encouraged the development of many areas of science and technology.

Ideas from physics were transformed into technology in record time, previously unknown to mankind.

Important advances were made in nuclear physics, elementary-particle physics, plasma physics, electrodynamics, solid-state physics, physical chemistry, electronics, and many other areas of physics.

The scientific foundations were laid and practical implementation followed in the areas of isotope separation, radiochemistry, the synthesis of chemical elements not occurring naturally, and radiation medicine and biology.

The extraction of purified plutonium-238 (an α emitter) from uranium bombarded by a neutron flux made it possible to create a safe, long-lived energy source for cardiac pacemakers. These devices have saved thousands of lives around the world.

Mankind has gained the fruits of a large number of the latest achievements in science, technology, and engineering, owing to the mastery of nuclear energy.

For fission it was necessary to obtain a sufficient quantity of highly enriched naturally occurring uranium-235 or to produce the highly enriched isotope plutonium-239 (not found in nature) in nuclear reactions.

Naturally occurring uranium contains 0.72% uranium-235. Various physical principles have been used to develop industrial methods of isolating concentrated uranium-235. These methods require a large amount of electrical energy.

To obtain plutonium-239 it was necessary to achieve a controlled nuclear chain reaction using natural uranium as the nuclear fuel, a neutron moderator made of a special quality of graphite, light water as a heat-transfer agent and simultaneously as a moderator, aluminum alloys as construction materials with minimal neutron absorption, and boron rods as intense neutron absorbers for regulating the neutron processes and thus the power of the converter. In the first converters the thermal energy released in the nuclear chain reaction was not used. The hot water from the converters was discharged into reservoirs.

After bombardment by the neutron flux in the converter, the natural uranium was discharged and processed radiochemically. The radiochemical processing of the bombarded fuel make it possible to separate plutonium isotopes. The isotopic mixtures in plutonium-239 were determined by the time of exposure of the natural uranium to the neutron flux.

The path toward the creation of the atomic bomb passed through the creation of isotope-separation plants, converters, and the field of radiochemistry.

The research performed in developing nuclear weaponry was used in the development of nuclear power sources.

The history of the fusion reaction is fundamentally different. The fusion of light nuclei (tritium plus deuterium) was first achieved in the atomic bomb. The energy obtained from the splitting of heavy nuclei created the conditions for the appearance of the fusion reaction. Achieving controlled thermonuclear fusion for power production turned out to be considerably more difficult than achieving controlled fission.

Achieving the fusion of a deuterium–tritium mixture requires heating the plasma to a temperature above 11.6×10^6 K (1 keV). For pure deuterium this temperature is above 10 keV. The final products of the fusion reaction, neutrons and helium nuclei, contain the entire kinetic energy of the fusion reaction. To have a nuclear chain reaction it is necessary that the plasma not be cooled by thermal losses.

In actinide nuclei, a nuclear chain reaction occurs at practically any temperature which technology is capable of reaching. In normal operation, most of the fission kinetic energy is contained in the solid fuel. The heat-transfer agent (coolant) removes this energy from the fuel.

The discharge of neutrons from the periphery of the active zone serves as the main regulator of the power of a nuclear reactor.

The useless loss of neutrons from the active zone of a fission reactor can be minimized by various methods.

A controlled fusion reaction can be achieved by using magnetic or inertial confinement of a plasma. A laser beam or an ion flux can be used to compress the target composed of a deuterium–tritium mixture.

Magnetic confinement of the plasma is most widely used around the world to obtain controlled thermonuclear fusion.

The compression of the target requires either a laser setup with high unit beam power or an accelerator of high unit power providing a high-energy ion flux. Both types of setup must be able to perform stable operation for hundreds of hours. At the present time there are no such setups, either laser or accelerator.

Achieving controlled thermonuclear fusion for energy production has proved to be considerably more difficult than achieving controlled fission. In the last forty years, despite the efforts of large groups of highly trained specialists in various countries (including Russia), it has not yet been possible to achieve a controlled fusion reaction useful for creating even a pilot energy generator. In spite of all our difficulties, we in Russia should not give up our research on controlled nuclear fusion.

The presence of the uranium-235 isotope in natural uranium made it possible to obtain a nuclear chain reaction. A real thermonuclear reaction requires tritium, which occurs in trace amounts in nature. Obtaining tritium by neutron bombardment of lithium-6 in a fission reactor has been studied.

If there were no uranium-235 in nature, could scientists still achieve fission and fusion chain reactions?

The minimally necessary amount of plutonium-239 can be produced by using an ion accelerator (whose operation requires electrical energy) to bombard uranium-238 with an ion beam.

The fast-neutron breeder reactor with efficiency greater than unity (using uranium–plutonium fuel) can be used as the basis for beginning the industrial production of plutonium-239, i.e., to develop large-scale nuclear power generation.

Ion accelerators can be used to produce tritium directly from lithium-6 by bombarding it with an ion beam. This is not energetically favorable. As soon as fission reactors are built, they can be used to produce tritium in any amount. After obtaining an ion flux of the required energy, it becomes possible to achieve a number of nuclear reactions.

Nuclear energy production based on the fission of actinide nuclei involves not only nuclear reactors and nuclear power stations, but also radiochemical plants, plants for preparing nuclear fuel—enriched uranium-235 and, in the future, high-background plutonium, and plants for preparing fuel elements and fuel assemblies. It also involves the transport of radioactive products over large distances.

It involves the problem of radiochemical waste.

It involves the problems associated with the induced radioactivity of nuclear reactors.

It involves the storage of radioactive waste from operational and repair work.

It involves the storage of spent fuel assemblies.

Nuclear power production will be far superior to other types of power production if every stage of the fuel cycle is maximally safe and if there is no danger to future generations from the release of radioactivity into the environment.

At the beginning of 1993, there were about 423 nuclear power plants operating in 28 countries, producing a total (unit) power of ≈ 330 GW. At present, another ≈ 70 nuclear power plants are under construction in 19 countries.

The basis for modern nuclear power production throughout the world is the PWR (pressurized water reactor) with varying unit power. There are about 239 such reactors producing a total (unit) electric power of ≈ 210 GW. The next most common is the BWR (boiling water reactor), of which there are about 89 producing a (unit) electric power of ≈ 73 GW. BWR reactors have not been constructed in the Soviet Union. Instead, RBMK channel water–graphite reactors were built.

The Soviet and foreign PWRs are based on the same scientific principles. Nuclear power plants based on pressurized water reactors are distinguished by the following: the quality of the manufactured equipment instrumentation; the quality of the structural and assembly work; electronic control systems; professionalism, discipline, and training of the operating personnel.

According to the data of the International Atomic Energy Agency, the best nuclear power plants in the world are those in Paksht, Hungary and Laviz, Finland. Soviet-made PWR-440 reactors are used in both of them. Hungary wants to construct another nuclear power plant. However, it appears that France rather than Russia will equip this plant. Discussions have been going on for many years about which type of reactor is best: the vessel or the channel type. In 1979 a serious accident occurred at the vessel-type reactor at Three-Mile Island in the United States. In 1986 a catastrophe occurred at the Chernobyl channel-type reactor in Russia.

Nuclear energy has become the subject of large-scale international political intrigue.

A crucial question at present is whether or not the building of nuclear power plants should be allowed in countries wishing to have their own nuclear arsenal. It is forbidden to transfer:

(1) The science and technology of the radiochemical processing of irradiated nuclear fuel for the extraction of plutonium.

(2) The science and technology of separating the isotope uranium-235 from uranium-238.

Nuclear power plants in foreign countries can use only uranium as fuel. Fuel enriched by plutonium cannot be sold. Plutonium can be extracted from such fuel by fairly simple chemical methods.

It is impossible to transfer the science and technology of fast-neutron reactors, which perform well the two principal tasks of generating electrical energy and producing artificial plutonium.

The fuel discharged from reactors must be returned to the supplier of fresh fuel. The fuel is taken to a radiochemical processing plant. The fission products are returned for burial to the country which bought the nuclear power plant. Radioactive actinides are left in the country of the fuel supplier for use in its own nuclear reactors. When spent fuel is not returned, the supply of new fuel is immediately stopped.

The question arises of whether or not it is possible in general to guarantee the nonproliferation of nuclear weapons. It is obviously impossible without the very careful monitoring of any operation directly or indirectly associated with nuclear reactions. Decisive measures to annihilate such installations must be taken swiftly and strongly. Here is one of the possible scenarios by which a country can create its own nuclear weapons:

1. It creates a highly professional scientific intelligentsia which sends talented young people to the best universities in the world.

2. It hires for 5–7 years, for a large amount of money, a small group of foreign, highly professional scientists, technicians, and engineers with practical experience in nuclear science and technology.

3. It orders individual components of installations it plans to build from various different countries.

The key problem is how to obtain fissile material, uranium-235, or plutonium-239, or uranium-233. It does not take much nuclear fuel to make several pieces of nuclear weaponry for the purpose of blackmail.

At present there are two fundamentally different approaches to dealing with the fuel discharged from nuclear reactors.

There is the closed fuel cycle. After a time delay which allows short-lived radioactive isotopes to decay, the discharged fuel is subjected to radiochemical processing to separate actinides from fission products. The actinides are sent to a nuclear-fuel processing plant to prepare them for reuse in a nuclear reactor. The amount of residual actinides left in the fission products should be as small as possible, as actinide half-lives are considerably longer than those of the fission products. After the processing required for long-term storage of radioactive wastes, the fission products are buried or sent to a monitored storage site. The closed fuel cycle allows the complete burning of not only all of the available mined natural uranium, but also of the depleted uranium left over from the weapons program. Fast-neutron breeder reactors and thermal-neutron reactors will operate using the closed fuel cycle. The closed fuel cycle can satisfy any electrical energy requirements of human society for a practically unlimited time.

At the present time, when electrical power production is dominated by the use of hydrocarbons, when much of the naturally occurring uranium has been mined for military programs, and when deposits of natural uranium have been explored and a fairly comprehensive technology for mining them has been developed, nuclear fuel enriched by uranium-235 is less expensive than nuclear fuel enriched by high-background plutonium.

Uranium, i.e., uranium fuel, cannot be used to create nuclear weapons without isotope-separation technology. This fuel is weakly radioactive and can be handled without any special, as yet undeveloped, technology.

The use of an interrupted fuel cycle involves the storage of spent fuel assemblies for a long time. The high-background plutonium which is produced remains packed in the nuclear fuel, which is placed in the metal sheaths of the fuel elements. This storage cannot continue indefinitely, and the spent nuclear fuel will eventually be subjected to radiochemical processing. The interrupted fuel cycle can be used only as a temporary measure (in small-scale nuclear power production). It lacks the radiochemical processing needed to ensure maximum safety in dealing with radioactive products, and, moreover, there is no protection from theft of plutonium by terrorists.

The current attitude of the United States government to nuclear power is based on the fear that plutonium, including plutonium discharged from water-cooled power reactors, can be used to create nuclear and radiological weapons. Back in 1962 a nuclear bomb in which the fissile material was high-background plutonium was built and tested in Nevada.

Plutonium is mortally dangerous also when used in bombs with ordinary explosive as dispersable radioactive material. A radiological war could annihilate every living thing in the region over which the plutonium is dispersed. Contact of plutonium with the lungs is especially dangerous. Owing to the long half-life of plutonium isotopes, the affected region would remain sterile for a very long time. It is practically impossible to collect or neutralize dispersed plutonium.

Plutonium can be annihilated by bombarding a plutonium target (not containing natural uranium) with a neutron beam.

Plutonium is required to enrich the start-up nuclear fuel in large-scale nuclear energy production using a closed fuel cycle. In the very near future, instead of storing the plutonium excess in special storage vaults, it will be possible to use it to obtain energy in nuclear reactors with maximum burnup fraction, moderate bulk energy output, moderate thermodynamical parameters, and optimized unit power with heat-transfer agent, i.e., in maximally safe reactors. In such a reactor, the plutonium is out of reach of evildoers and generates heat and electricity.

The position of the United States regarding the use of high-background plutonium in nuclear power plants is influenced by the following factors.

1. The cost of natural uranium on the world market is low, owing to the slow rate of introduction of nuclear power reactors into energy production and the large known deposits of natural uranium.

2. The cost of the radiochemical processing and preparation of fuel enriched with high-background plutonium, and of the handling of fission products, is high.

In summary, at present in the United States there is no economical advantage in switching from the familiar uranium-uranium fuel to plutonium-enriched uranium.

3. The radiochemical processing involves radiation and nuclear hazards. There is also the possibility of plutonium theft during the extraction of plutonium from spent fuel and the preparation of fuel elements.

The storage of spent nuclear fuel in the form of fuel assemblies forever is senseless. At any time the United States can subject these assemblies to radiochemical processing.

4. Owing to the abundance in the United States of native and inexpensive imported hydrocarbon fuel, there is no rush to change over to the use of the closed fuel cycle in nuclear power generation.

The governments of Russia, France, Britain, Japan, and India think that in the long run, nuclear power production will sooner or later (depending on the rate at which it is introduced into electricity generation) have to rely on nuclear fuel enriched with high-background plutonium.

Since December, 1942, when Fermi succeeded in obtaining the first nuclear chain reaction in the world, the previously unknown spectre of nuclear and radiation danger has haunted every living thing on Earth. Fermi himself became one of the first victims of radiation.

The United States and the Soviet Union, competitors in the race to create nuclear weapons and, at that early period, lacking information about the effect of radiation on living organisms, grossly violated the conditions for safety in working and living around radiation.

For example, there are the victims of Hiroshima and Nagasaki, the victims of nuclear weapons testing on land, in the atmosphere, and in the oceans, and the victims of war maneuvers of armies using nuclear weapons.

There have been accidents at Windscale in England and at Three-Mile Island in the United States, and the Chernobyl catastrophe in the Soviet Union.

There have been less serious accidents involving nuclear submarines. They have led to severe radiation sickness and the death of operating and clean-up personnel.

There is the effect of radiation on operating personnel and researchers in accidents which have occurred at critical assemblies, research reactors, converters, energy reactors, and radiochemical plants.

There is the overexposure of personnel performing maintenance and repair work.

In the early years of nuclear weapons production the lives and health of workers were endangered owing to the lack of understanding of dosimetry and the inadequately protected handling of plutonium and tritium.

Over the years, large amounts of radioactive material have been dumped in rivers, lakes, and oceans. Parts of the Earth have been polluted by radioactive products.

Underground nuclear explosions have sometimes been accompanied by the release of radioactivity at the Earth's surface.

All of these various events have made the average person (who is, of course, the most important) anywhere in the world aware of this incomprehensible thing called nuclear energy. The mortal danger of nuclear energy has become obvious to him, and he does not see what use nuclear energy is to him.

What are the real, positive benefits of nuclear energy to mankind?

1. It provides an unlimited, concentrated source of energy for generating electricity.

The energy content per unit mass of nuclear fuel is a million times greater than that of hydrocarbon fuel, and so the energy production is independent of the distance to the uranium mines.

The advances which have already been made will allow the next generation of nuclear power plants and the fuel cycle to be made maximally safe and economically advantageous.

Nuclear energy can provide the primary source of electricity and thereby lead to the economical use of the unique natural hydrocarbon energy sources, oil and natural gas, the natural reserves of which are finite and without which modern society, in principle, cannot survive.

In the future, all aspects of nuclear power production can be made less harmful to man and the environment than energy production based on hydrocarbons. Electric power stations will not dump large amounts of carbon dioxide into the atmosphere. A large fraction of land and air transport can be designed to run on hydrogen fuel, using nuclear energy to obtain inexpensive hydrogen. All rail transport can be electrified.

2. It makes it possible to have a submarine and surface fleet of unlimited range for peaceful and defensive purposes.

3. It allows the creation of energy generators for space flight to distant planets of the Solar System. It allows the establishment of colonies on these planets. Solar radiation cannot provide a source of energy on these planets.

4. The existence of modern nuclear and thermonuclear weapons ensures the nonagression of potential enemies, independence, and territorial integrity. The threat of punishment by nuclear weapons decreases the possibility of a world war.

5. The possibility in principle of a collision between a cosmic body of significant mass and the Earth or another planet is not excluded. Such a collision could annihilate all life on Earth. The timely discovery of such a body and the setting off of nuclear explosions on it could change its trajectory and save the Earth.

Whereas in the Soviet Union the average person was not taken into consideration when choosing sites for peaceful and military nuclear installations, now in modern Russia nuclear power plants can be constructed only if it is possible to convince the population that all aspects of nuclear energy are extremely safe and even safer for the health of people and Nature than coal-based energy production. A nuclear power plant provides people with prestigious, well paid employment and modern, free, specialized medical services. The conditions for a comfortable life are created.

The approach to constructing nuclear power plants must be fundamentally changed. It is necessary to have a technical and economic power base and time to get the power plant running. The inhabitants of the area where it is located must be educated about all aspects of the operation of the plant and encouraged to express their thoughts.

The real dangers associated with nuclear energy, magnified by secrecy and rumors, have led to the formation of groups of people of diverse professions, religious beliefs, and convictions who oppose not only the nuclear weaponry which can annihilate mankind, but also nuclear power.

The groups and individuals opposing nuclear energy often have a poor understanding of it. It is necessary to deal with them using facts, and not general arguments. It is necessary to carry out a serious dialog, without resorting to dictates. These opponents have a great deal of common sense. They make professionals think, and this leads more directly to the creation of maximally safe nuclear power production. The pseudo-patriots are more dangerous, and following their lead can lead to another catastrophe like that at Chernobyl.

Discussions with opponents of nuclear energy should be based on the following facts:

1. The highly professional basis on which it is possible to realize nuclear power production which is maximally safe in all aspects of the closed fuel cycle.

Radioactive waste including the entire possible range of isotopes must undergo processing to transform them into either short-lived isotopes or isotopes with very long half-life, or to completely destroy the nuclei of a highly radioactive isotope. The isotopes which cannot be transmuted must be treated and stored in such a way that under no conditions can they escape into the environment.

Nuclear energy plants and the entire fuel cycle must be guaranteed to be protected from personnel errors, natural disasters, and terrorism. There must be protection from fire and from chemical and vapor explosions.

There must be no emission of radioactivity into the environment during radiochemical processing.

2. In a given geographical region, beginning at a given time, a nuclear power plant of a given power output will be economically and ecologically more sound than any other type of power plant based on the use of hydrocarbon fuel.

The principle that plants which pose a great danger to the health and life of the operating personnel and the environment will be constructed only in very extreme, hopeless situations must triumph. It is necessary to seek alternative solutions which make such plants unnecessary. If all aspects of nuclear power generation cannot be made safe, it will be necessary to rely on the large-scale use of coal and to intensify the research on the use of solar radiation and the design of batteries capable of storing large amounts of energy.

At the present time, the science of nuclear power engineering faces the following problems.

There must be continued gradual improvement of existing nuclear energy installations—light-water-cooled thermal-neutron reactors—in order to ensure accident-free operation until their planned shutdown. The nuclear fuel in these reactors is used in the interrupted fuel cycle, without radiochemical separation of the discharged fuel or return of high-background actinides to the fuel cycle. It is impossible to use thermal-neutron reactors for large-scale energy production. Less than one percent of the mined natural uranium can be consumed in such reactors. However, during the initial period of development of nuclear power production, individual developed countries could permit themselves to rely on nuclear power generation using only thermal-neutron reactors.

In fast-neutron breeder reactors, the nuclear reactions transform the natural nuclear raw material, uranium-238, into artificial nuclear fuel—plutonium. When a breeder operates in the energy mode, it produces more plutonium than it consumes. There is more plutonium in the discharged fuel from a breeder reactor than there was in the original fuel.

There must be as little neutron slowdown as possible in the active zone of such a reactor. The water moderating the neutrons in principle cannot be a heat-transfer agent which removes energy in the active zone of the reactor, where the nuclear reactions occur.

The maximum consumption of uranium-238 is the basis for large-scale nuclear power production. Owing to their nuclear-physical, physical, and thermomechanical parameters, the nuclear fuel elements currently used cannot consume all the fuel they contain. After the maximum possible fuel depletion, the fuel elements undergo radiochemical processing. This processing removes the neutron-absorbing fission products from the nuclear fuel isotopes, and the nuclear fuel is returned to the reactor in the form of new fuel elements.

The longer uranium-238 is bombarded by neutrons, i.e., the longer the fuel elements remain in the active zone, the greater is the quantity of heavy isotopes produced. The higher the radioactivity of the discharged fuel, the more complicated is the radiochemical processing. The possibilities offered by radiochemical processing must be taken into account when determining the burnup fraction of nuclear fuel. The relation to the closed fuel cycle is different at different stages of development of nuclear power production.

It would be very tempting to have a burnup fraction in the fuel elements such that the discharged fuel did not have to undergo reprocessing, because too few combustible and raw isotopes remained in it. The discharged fuel could then be stored under observation without damaging the fuel elements and could be subjected to commercial transmutation, i.e., bombardment by high-energy ions to annihilate the radioactive isotopes. The need for radiochemical processing would disappear. This goal is so attractive that sooner or later in-depth theoretical research on fuel elements must be carried out together with experimental verification. The possibilities offered by fuel elements in thermal- and fast-neutron reactors regarding their fuel composition, construction material, temperature conditions, energy release, and burnup fraction must be understood.

Large-scale nuclear power production must rely on the closed fuel cycle with radiochemical processing of the nuclear fuel. Such energy production must also involve a significant number of reactors: fast-neutron breeder reactors. Only liquid metals can be used as the heat-transfer agent in such reactors. To increase the reliability of the operation of breeder reactors, the energy intensity in the active zones of these reactors must be lower than proposed earlier, when high breeding ratios were being sought. This means that there must be many such reactors in order to obtain a given amount of plutonium. Large-scale energy production, if we want it, unavoidably requires fast-neutron reactors with liquid-metal cooling. In order for the entire infrastructure of building and operating nuclear-energy installations not to collapse, on moderate scales it will be necessary to continue the construction of new water-cooled reactors taking into account all the ways in which they can be improved.

Owing to the features of water as a heat-transfer agent, water-cooled nuclear reactors cannot form the basis of safe nuclear power production, no matter what tricks their designers come up with.

The reliability and operational safety of water-cooled reactors can be improved by:

(a) optimizing the unit power of the reactor;

(b) decreasing the bulk energy release as much as possible;

(c) providing a sizable margin before reaching a boiling crisis in all operating modes;

(d) using natural circulation (a system without pumps) in the nominal power mode;

(e) shielding the steam generator from large leaks;

(f) placing, inside the reactor vessel under the active zone, a pan for a damaged fuel assembly containing incident fragment splitters and neutron absorbers;

(g) locating two control sensors operating on different physical principles at each critical point;

(h) providing self-shielding of the control systems from operator error and sabotage;

(i) introducing continuous automated monitoring of the quality of the water of the primary and secondary circuits, and introducing continuous monitoring of the appearance of radioactivity in the secondary circuit in the region of the steam generators.

The radiolysis occurring in the normal operating mode of a nuclear power reactor which does not operate at high temperatures causes chemical compounds to break down. Chemical elements are produced in the atomic state and possess high chemical activity. If there is reactor radiation, nothing can prevent radiolysis from occurring.

The effect of the products of radiolysis on the materials of the primary circuit can vary, depending on the chemical compound selected as the coolant and on the energy of the reactor radiation. In an emergency situation, when temperatures can become very high, pyrolysis comes into play along with radiolysis in breaking down chemical compounds.

The lack of understanding of the constraints imposed by radiolysis and pyrolysis has led to misguided attempts to use hydrocarbons and CO_2 and N_2O_4 gases as coolants.

The attempt to use N_2O_4 in a one-circuit scheme in a fast-neutron reactor involved fundamental errors:

(1) The breakup of N_2O_4 molecules provided the basis of an original design for intensifying the energy removal in the active zone, but the fact that atomic oxygen creates an extremely corrosive environment was not taken into account. Oxides of the construction materials clogged up the passages in the active zone. A sharp decrease in the flow rate of the coolant resulted. None of the techniques for cleaning the N_2O_4 gas worked or could work. The creation of construction materials possessing satisfactory nuclear-physical characteristics and which are stable at high temperatures in atomic oxygen is problematic and would make the cost of the reactor too high. The nuclear fuel most widely used at present, uranium dioxide, is oxidized in an oxygen medium to U_3O_8. The oxidized fuel breaks the casing of the fuel element because its volume is increased upon oxidation. Nonhermeticity of the fuel elements in an N_2O_4 medium leads to damage of the fuel elements. It was necessary to develop a special fuel which is stable in an environment of atomic oxygen. For a breeder reactor, which must operate using a closed fuel cycle, this would greatly complicate the radiochemical processing.

(2) The nuclear-physics characteristics of nitrogen and oxygen made it possible in principle to create an active zone for fast neutrons, i.e., to design a breeder based on fast neutrons, which could compete with the sodium reactor. However, in fast-neutron reactors, which are systems with high-intensity energy output, low heat capacity of the active zone, and high enrichment of the nuclear fuel, it is impossible in principle to use a gaseous coolant, which in an emergency situation could escape from the active zone.

(3) If a miracle occurred and a fast-neutron reactor using N_2O_4 coolant did function, the reactor would become a producer of tritium, which would easily diffuse outside the circuit through the hot walls of the circuit:

$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{12}_{6}C + ^{3}_{1}T.$$

Naturally occurring nitrogen has the isotope mixture 99.635% $^{14}_{7}N$ and 0.365% $^{15}_{7}N$.

Beginning in 1947, British scientists carried out scientific research and experimental and structural studies on nuclear reactors using graphite as the moderator and carbon dioxide gas CO_2 as the coolant.

In spite of all the efforts of highly professional specialists, the work led to a dead end. It could not have happened otherwise. CO_2 cannot perform as a coolant in a nuclear power reactor in which radiolysis and pyrolysis occur.

In the 1950s and 60s studies were carried out in a number of countries on the use of hydrocarbon compounds as the coolant in nuclear power reactors. These studies were stimulated by the desire to find a coolant which could perform at low working pressures, which is not possible with liquid water. Under the action of pyrolysis and radiolysis the original hydrocarbon compounds were destroyed, and new compounds possessing different chemical and thermophysical properties were formed. On the surface of the fuel elements, the hottest point of contact between the coolant and the heat-emitting surface, there appeared a stable film of low thermal conductivity composed of the products of radiolysis, pyrolysis, and corrosion. This deposit raised the fuel temperature and shrank the coolant passages. The nuclear power plants could not operate in this mode. The work on organic coolants was halted.

The physical foundations of all modifications of water-cooled reactors are the same everywhere in the world.

At the present time, nuclear power plants are being made safer by improving and increasing the number of protective barriers, by perfecting the systems which measure and monitor the neutron and thermal processes occurring in the reactor, by creating control systems which are self-shielded from operator error and sabotage, and by improving the quality of the operation. All these measures are certainly important, but they cannot fundamentally improve the safety of a nuclear power plant.

Light water used as the coolant in a nuclear reactor can, under extreme conditions, lead to a serious accident. There are no engineering methods which can make water reactors completely safe.

By the time the first nuclear power plants were built, a great deal of experience had been accumulated in using light water in thermal power engineering. It was natural to use light water in designing nuclear energy plants. The nuclear-physics parameters of light water are such that it can perform as a good neutron modulator, and so it can play the dual role of coolant and moderator in thermal-neutron reactors. The water in such reactors does not undergo radiolysis or, in practice, pyrolysis. Water does tend to enhance corrosion when the heat production reaches high thermodynamical parameters. Nothing was known about how water behaves in accidents at nuclear power plants. Strictly speaking, sufficient attention was not paid to accidents in the early stage of designing nuclear power plants. Thermal power engineering did not possess any coolant other than water. If the designers of the first nuclear power plants had focused on seeking better coolants, the construction of the first nuclear power plants would have been greatly delayed. In the case of fast-neutron reactors, where water in principle cannot be used, the initial design efforts involved a search for coolants. The first coolant used in fast-neutron reactors was mercury, followed by sodium–potassium eutectic; finally, sodium was chosen. Light water is used as the coolant in most modern nuclear power plants for generating electricity and in nuclear-powered submarines.

As more experience was gained, it became clear that light water can create emergency situations in nuclear power plants and that it cannot alleviate an accident once it starts. It became clear that during an accident at a nuclear power plant, operating at process rates, temperatures, and pressures previously unknown in thermal power engineering, it can happen that water, a chemical compound of oxygen and hydrogen, begins to act as an oxidant.

The use of light water as a coolant does not allow the creation of maximally safe nuclear power production for the following reasons.

1. The low boiling point of water at atmospheric pressure. Nuclear power plants are designed to use high pressures. The maximum temperature of the water in a pre-thermodynamical crisis situation is +374 °C at a pressure of 225 atm. Violation of the hermeticity at any point of the primary circuit leads to coolant loss. The accumulated thermal energy of the active zone and the residual heat release in the nuclear fuel in the shut-down reactor cause the water to evaporate.

In water–water reactors the loss of water due to violation of hermeticity causes the nuclear chain reactions to stop, because the moderator disappears. However, the coolant also disappears. There is nothing to remove the residual heat release and the accumulated heat of the nuclear fuel.

Leaks in the steam generators are especially dangerous in reactors of the PWR type. All the water can be lost if a sizable leak develops and the shut-off system fails. There are no water reserves sufficient for emergency cooling. The radioactive water escapes into the building housing the reactor.

2. The boiling crisis. When one or several of the parameters affecting the intensity of the heat removal—the unit thermal flux, the water flow speed, the pressure—are changed, or the water is underheated below the saturation or vapor-content temperature, bubble boiling can disappear. A hot surface becomes covered with a vapor film. The vapor film will not only fail to step up the heat removal, which bubble boiling achieves, it will actually create additional thermal resistance. The temperature of the fuel will rise sharply.

At the present time, zirconium alloys are widely used for the casings of fuel elements. Zirconium alloys have good nuclear-physical parameters and react weakly with water at temperatures up to 400 °C. The temperature at which chemical interaction starts and the strength of the interaction depend on the energy released in this interaction and lost to the surrounding medium. The energy reaching the reaction zone from outside (from other energy sources) intensifies the interaction.

The heat flux from the nuclear fuel passes through the casings of the fuel elements to the coolant. Zirconium begins to interact strongly with water vapor at casing temperatures above 800 °C. The oxygen goes into oxidation of the zirconium, and the hydrogen moves into the spaces occupied by the coolant. The oxidation of the casing causes it to disappear. Oxides of zirconium are not mechanically stable. The nuclear fuel located inside the zirconium tubes is no longer held in place and collapses. The contact between the uranium dioxide of the nuclear fuel and the water vapor at high temperatures leads to oxidation to U_3O_8.

The free hydrogen liberated in the oxidation of zirconium and uranium oxide forms a gas bubble which is dangerously explosive if it comes into contact with air. The hydrogen bubble further impedes the cooling of the nuclear fuel.

The boiling crisis can lead to deterioration of the heat removal so severe that the fuel elements melt fairly rapidly.

3. A vapor explosion. The nuclear fuel used at the present time, UO_2, has a high temperature under normal operating conditions and accumulates a great deal of heat energy, owing to its low thermal conductivity. The residual heat release in the shut-down nuclear reactor also contributes to heating of the fuel with impeded cooling.

The abrupt increase in the area of contact of nuclear fuel fragments with water residues in and under the active zone leads to dangerously explosive boil-up of the water.

The situation can deteriorate if the fuel elements are damaged as a result of an accidental rise in the energy release in the reactor. A vapor explosion can lead to the following:

(a) It can tear off the reactor cover and the components of the emergency shielding and power regulators. All the water would leave the active zone. A nuclear explosion can occur in the remaining nuclear fuel.

(b) The reactor housing and the tubing of the primary circuit can be destroyed. Water would begin to rapidly leave the active zone, evaporating under the reactor container.

Cracks which were formed in the process of constructing the reactor housing and which cannot be detected by existing flaw detectors can cause the vessel to break when the pressure rises sharply.

(c) The steam generators can be destroyed.

(d) The regulatory devices and emergency shielding can be destroyed without loss of hermeticity of the primary circuit.

(e) The active zone can be destroyed.

The natural question arises: is it possible to construct a nuclear power plant which in principle is maximally safe, or, can we arrive at the point where the methods of increasing the safety are exhausted?

The main principles which can ensure the maximal safety of nuclear reactors.

The following practical solutions are now available.

(1) A design of the active zone of the nuclear reactor in which the nuclear chain reaction is self-quenching in the event of an accidental temperature rise in the elements of the active zone, without affecting the emergency shielding.

(2) Safeguards to ensure that the energy released by the nuclear fuel corresponds to the amount of energy which can be removed. If such safeguards are implemented, even in emergency situations there will be no overheating of the fuel or damage to the fuel elements.

(3) Coolants with good nuclear-physical properties. The physical and physico-chemical properties of the coolant must not be affected by the reactor radiation. In an emergency high-temperature situation the coolant should not become chemically active. At the working temperatures of the nuclear reactor the coolant should not heat up when coming into contact with air. A vapor explosion of the coolant in the active zone would not occur in an emergency situation, owing to the high boiling temperature and the high heat of vapor formation of the coolant. The coolants of nuclear power reactors can be chemical elements, but not chemical compounds. All chemical compounds undergo radiolysis and pyrolysis to a greater or lesser degree.

(4) The heat stored in the nuclear fuel in the power-producing mode and the residual heat release due to nuclear processes occurring even in a shut-down reactor can destroy the fuel elements if the coolant is lost. The coolant of a nuclear reactor in the operational mode must be under pressure which prevents it from escaping or boiling up in the event that the hermeticity of the circuit is violated. There are engineering techniques for constructing a nuclear reactor such that the active zone will never dry out. Even in the most severe accidents the coolant does not leave the active zone.

(5) To minimize the severity of an accident, it is necessary to optimize every newly built nuclear reactor in the unit reactor power, the bulk energy release, the thermodynamical parameters, the quantity of the input fuel, the enrichment of the fuel, the burnup fraction, the thermophysical parameters of the nuclear fuel, the nuclear-physical, physico-chemical, and thermophysical parameters of the coolant, the amount of coolant in the primary circuit, the nuclear-physical, physico-chemical, and thermomechanical properties of the construction materials from which the reactor is built, and the quantity of these materials. The optimization must take into account economic and ecological factors.

Helium as a coolant for nuclear power reactors.

Helium possesses excellent nuclear-physical parameters.

Helium is not activated in reactor radiation fields.

Owing to its chemical inertness, there are no problems of helium interacting with the nuclear fuel, fission products, or construction materials.

Helium does not interact with the oxygen in air and in water. Vapor explosions are impossible.

A one-circuit reactor design can be used in which helium heated in the reactor will produce energy in a gas turbine.

The main drawback of helium is the high pressure at which it becomes a good heat conductor. Violation of the circuit hermeticity can lead to complete loss of the helium.

In the event of loss of hermeticity of a helium-cooled reactor, air can enter through an opening into the active zone. The oxygen of air can oxidize the heated elements of the active zone.

For a thermal-neutron helium–graphite reactor with optimized unit power, the complete loss of the helium is not catastrophic. Such reactors have low bulk energy release; large masses of graphite at the high sublimation temperature of graphite; the high thermal stability, heat capacity, and thermal conductivity of graphite; and self-quenching of the nuclear chain reactions when the graphite is overheated. Owing to all these factors, such a reactor may not be damaged even for complete loss of the helium. After heating to the equilibrium temperature, the nuclear chain reactions quench themselves and there will be only residual heat release. The discharge of heat to the surroundings is stabilized.

The thermal-neutron helium–graphite reactor satisfies the requirements of maximal safety. However, helium cannot be used for fast-neutron reactors, even though the use of helium coolant in a fast-neutron reactor would give the maximum breeding ratio. In a fast-neutron reactor, loss of the helium would lead to meltdown of even the dead zone, owing only to the residual energy release. In the active zone of a fast-neutron reactor there is no mass which could, owing to its heat capacity, carry off the released energy. The active zones of such reactors are high-intensity zones. The fuel is at a high temperature in the operational mode. The fuel of fast-neutron reactors is highly enriched. Meltdown of the active zone of a fast-neutron reactor would lead to a catastrophic release of radioactivity. Meltdown of the highly enriched fuel would lead to the formation of an uncontrollable critical mass with all kinds of serious consequences. It would be senseless to construct a fast-neutron breeder reactor using a gaseous coolant.

Nuclear power engineering underwent intensive development throughout the world in the 1960s. A large quantity of nuclear fuel was needed as soon as possible. It was possible to obtain uranium-235 from isotope-separation plants and to produce plutonium in nuclear reactors.

It was necessary to construct fast-neutron breeder reactors. In trying to make as much plutonium as possible in such a reactor, it was necessary to design these reactors such that they had high-intensity active zones. The thermal energy released per unit mass of the nuclear fuel is limited by the ability of the coolant to carry off the energy. The decisive factor is the maximum attainable fuel temperature for coolant temperature at the reactor output acceptable for producing electricity.

The required heat removal in the normal operating mode, the start-up mode, and the possible emergency modes is the main factor determining the choice of coolant (which should also have good nuclear-physical parameters) for fast-neutron reactors.

In the initial stage of breeder construction, sodium, lithium-7, and helium were considered as coolants. Lead–bismuth eutectic and lead were not considered for large-scale power production, because they are inferior to sodium and lithium in their thermophysical parameters. At that time the behavior of the coolant in the event of a serious accident was not given sufficient attention.

Lithium-7 coolant. Lithium-7 possesses satisfactory nuclear-physical properties and record-setting thermophysical properties.

Its melting point is 180.5 °C.

Its boiling point is 1347 °C.

Its heat of vaporization is 19.6×10^6 J/kg.

Its thermal conductivity at 1000 °C is 53.6 W/m °C.

The use of lithium is associated with tritium production when lithium is exposed to neutron fields. It is practically impossible to contain tritium within metal walls at high temperatures. This makes lithium unusable for steady-state power production.

It will be possible to make rational use of lithium in blanket hybrid thermonuclear reactors, as it is an excellent coolant and producer of tritium for thermonuclear reactions.

Lithium is the lightest metal: $\rho=0.44$ kg/l at 1000 °C. Lithium is the best coolant for high-power reactors used in space flight. The tritium losses through the heated walls obviously pose no problem in outer space.

Liquid-metal coolants can be used at low pressure, the pressure produced by the circulation pumps which move the coolant. Liquid-metal coolant temperatures of 500–600 °C have been mastered. When lithium coolant is used the temperature can reach about 1000 °C. The main problem that remains is how to create construction materials which can be used with lithium at these temperatures. Liquid-metal coolants allow the design of nuclear power installations with thermoelectric or thermoemission conversion. It is possible to construct a steam turbine operating on potassium vapor (boiling temperature 760 °C) or cesium vapor (boiling temperature 670 °C).

In the case of conveyer installations, the use of liquid metals can provide record-setting weight/size characteristics for practically any unit power.

Large-scale nuclear power production should be based on a reasonable combination of fast- and thermal-neutron reactors. A monopoly of water-cooled thermal-neutron reactors operating in the interrupted fuel cycle is in principle excluded in large-scale nuclear power production. There is no need to become attached to water-cooled thermal-neutron reactors. They have made their contribution to nuclear power production and should continue to exist a bit longer, while gradually giving way to maximally safe nuclear reactors.

Liquid metals as coolants have no competition. Liquid metals make it possible to obtain high efficiency in steady-state energy production.

The present water-cooled nuclear reactors have efficiencies of about 33%. Modern reactors with sodium cooling have efficiencies of about 40%. This means that they produce a given amount of energy while burning less nuclear fuel. They produce fewer radioactive fission products. Nuclear power production on a large scale will produce less thermal contamination of the environment.

Sodium coolant. The use of sodium as a coolant (and sodium is the best studied coolant) provides heat removal for high bulk energy release and thereby (if needed) can ensure a high plutonium breeding ratio.

There is a great deal of worldwide experience in the construction and use of fast-neutron reactors with sodium coolant. Examples are the EBR-2 reactor (United States), the BOR-60, BN-350, and BN-600 reactors (Soviet Union), the PFR reactor (Britain), and the Phenix and Superphenix reactors (France). The BN-350 reactor was designed in a loop configuration, i.e., it is similar to water-cooled devices, where the coolant is under high pressure and it is impossible to have large amounts of coolant in the primary circuit. The special ability of liquid-metal coolants to sustain high temperatures at low pressure was not exploited in that reactor. However, the BN-600 reactor was designed to have a reservoir configuration, with the active zone, pumps, and metal–metal heat exchangers located in a large volume of sodium. The ability of liquid metals to sustain high temperatures at low pressures was fully exploited in the construction.

Natural sodium consists of the single stable isotope $^{23}_{11}Na$.

Two radioactive isotopes are produced in neutron fields: $^{22}_{11}Na$ ($\tau^{1/2}=2.6$ yr) and $^{24}_{11}Na$ ($\tau^{1/2}=15$ hr).

The melting point is 97.8 °C.

The boiling point is 886 °C.

The heat of vaporization is 3.9×10^6 J/kg.

The thermal conductivity at 700 °C is 58.9 W/m °C.

The density at 700 °C is 0.75 kg/l.

It is chemically active.

It reacts violently with water.

It is a fire hazard.

The oxide layer on the surface of stainless steel determines the stability of the steel in aggressive media. Sodium is more active than the components of stainless steel. Stainless steel loses its oxide layer in liquid sodium. The stability of the steel is determined by the solubility of the components of stainless steel in sodium at the operating temperatures.

The flux of liquid sodium is contaminated with "dirt": sodium oxides, sodium hydrides, corrosion products, fission products, and actinides from defective fuel elements.

The nuclear reactor has zones of high and low temperature and large and small velocity, and stagnant zones. The temperature and hydrodynamical regimes vary with the reactor power. The circuit has a cold trap for cleaning the sodium coolant and a periodically operating dirt indicator. There is no assurance that all the dirt is concentrated only in the cold trap and is not present in other parts of the sodium circuit, that the dirt does not move around, and that under unfavorable conditions it cannot hinder the flow of coolant in the active zone. In a system with parallel channels an obstruction of an individual channel cannot be found. Once the circuit has become contaminated, even an extensive cleaning of the sodium by the cold trap does not guarantee that the dirt has been completely removed from the active zone.

The study of the behavior of dirt in the sodium flux is so important that a special device was used to record the removal of the accumulated, uncontrollable dirt clogging up part of the passages of the active zone.

Intense formation of sodium oxides can occur in the event of an accidental leak of atmospheric oxygen into the circuit. This has occurred at the Superphenix reactor. The lack of a continuously operating oxygen indicator and the large amounts of liquid sodium led to a significant release of air into the primary circuit of the reactor, which was eventually found by a periodically operating indicator.

Designing an indicator for oxygen in sodium is not simple. There is no experience in this area. Such an indicator must be created to ensure the safe operation of sodium circuits.

The contamination of the sodium by machine oil is very dangerous. Such an accident occurred at the PFR reactor in Britain. When combined with liquid sodium, the oil forms coke and gaseous hydrocarbons. The coke can clog up passages of the active zone and can be deposited on the tubing of the fuel elements, creating additional thermal resistance. The passage of a sufficiently large amount of hydrocarbon gas through the active zone can give rise to a positive vacuum effect. The instrumentation in contact with the sodium in principle must not contain any systems using oil.

A danger for fast-neutron reactors with liquid-metal coolant is the formation, for a variety of reasons, of voids (regions not containing sodium) in the active zone.

The appearance of a void affects the reactivity of the active zone. A positive vacuum effect in the reactivity—a local energy-release burst—can arise. The cooling of the fuel elements in the bubble region abruptly deteriorates. The temperature of the fuel elements can reach damaging levels.

The working temperature of the sodium at the exit of the cassette of the active zone is about 550 °C. The margin before sodium boiling begins is small, about 300–350 °C. In an emergency situation a decrease of the flow rate of the sodium in the cassette causes the sodium to begin to boil. A vapor bubble affects the sodium flow rate, decreasing it further. The vapor bubble induces a change in the reactivity of the active zone.

If fuel collapse occurs as a result of the accidental meltdown of fuel elements, the following can arise:

(a) A sodium vapor explosion. A low-intensity explosion can have very serious consequences in a reactor with a reservoir configuration which is not designed for high pressures.

(b) The collapse of a significant quantity of highly enriched fuel can lead to the formation of an uncontrolled critical mass of nuclear fuel. The timely detection of a rise in the sodium temperature and, accordingly, the formation of a void in the cassettes requires at least two temperature sensors, based on different physical principles, on each cassette. The temperature sensors warn of an increase of the temperature of the sodium discharged from the cassette. Thermometry can detect the appearance of a vapor bubble before a reactivity meter can.

Nuclear-physical optimization can in principle solve the problem of the possible appearance of a positive vacuum reactivity coefficient. The device can be made weakly sensitive to voids.

The interaction of sodium with water. Sodium interacts violently with water, giving off free hydrogen. Measures must be taken to prevent the hydrogen from coming into contact with the oxygen of air. The products resulting from the interaction of sodium with water lead to corrosion of the steel located in the interaction zone. Owing to tubing of poor quality in the steam generators, in the initial stage of start-up of the BN-350 reactor there were large water leaks into the sodium of the secondary (nonradioactive) circuit. The personnel involved in the start-up of the reactor dealt honorably with the leaks: they repaired the steam generators and got the reactor operating at the designed power.

In principle, the entrance of water into the active zone of a fast-neutron reactor is unacceptable. The presence of water vapor or products of the interaction of sodium with water leads to clogging of the passages of the active zone and can result in a nuclear burst. Fast-neutron reactors with sodium coolant require an intermediate circuit separating the active zone from water.

The cost of the power produced by nuclear reactors with sodium coolant is higher than that produced by two-circuit water-cooled reactors, mainly owing to the three-circuit design. In the three-circuit design, even a very severe accident involving the steam generators does not lead to a nuclear accident. The higher cost of the three-circuit design is the price paid for safety. All the schemes for replacing the three-circuit design in fast-neutron reactors with sodium coolant by a two-circuit design have failed. Breakdown of a steam generator in a water-cooled reactor, which can lead to dehydration of the active zone, is just as dangerous as an accident occurring at a reactor with sodium coolant. However, no one anywhere in the world has yet found any fundamental measures for protecting the active zone from dehydration in the event of breakdown of a steam generator in reactors of the PWR type. The lower price of the power from the PWR reactor compared to the BN reactor comes with increased risk of an accident in the former, owing to the lack of a three-circuit cooling system. The designs for water-cooled nuclear power generators in submarines must satisfy stringent weight/size requirements. The three-circuit design has led to the appearance of water–water heat exchangers. As a result, the already low temperature of the water delivering heat in the steam generators is decreased. Additional circulation pumps have appeared. The weight/size characteristics of the steam generators have deteriorated. The direct transfer of the two-circuit design to steady-state reactors has created a certain risk of accidents in the operation of the latter. Fast-neutron reactors with sodium coolant did not have any military prototype. The BN reactor was originally designed to use the three-circuit scheme for steady-state power production.

Sodium fires.

The burning of sodium releases an energy 1.9×10^7 J/kg (the burning of benzene releases 4.39×10^7 J/kg). The temperature rises in the boxes where the sodium begins to burn. The pressure then rises, which can destroy the box. A caustic smoke is produced. Radioactive sodium fires are the most dangerous, as they always contain not only radioactive sodium isotopes, but also elements with induced radioactivity, fission products, and actinides from nonhermetic fuel elements.

If the sodium spills out into an area containing even a small amount of water, microbubbles appear and disperse the hot sodium. The hydrogen formed when sodium reacts with water explodes.

In December, 1995 at the nuclear reactor Manju, the first fast-neutron reactor with sodium cooling in Japan, a sodium leak developed in the secondary (nonradioactive) circuit.

Two to three cubic meters of sodium flowed into the box. The sodium was ignited.

Sodium fires in testing facilities and nuclear reactors have occurred in the Soviet Union, France, Britain, and the United States, but there was no combustion of an amount as great as in Japan.

Extinguishing a sodium fire is dangerous and inefficient. Such fires are accompanied by the release of an amount of heat per unit mass similar to the burning of coal, explosions which disperse hot sodium, and the appearance of caustic sodium which burns the lungs, mucous membranes, and skin of people in the vicinity of the fire.

To localize large amounts of sodium and prevent it from burning, it is necessary to have a way of pouring the sodium from the affected circuit into special hermetic storage vessels, thereby stopping the discharge of sodium from the circuit into the fire zone.

The Manju nuclear reactor has a loop design similar to that of pressurized water-cooled reactors. The amount of sodium in the primary circuit is not large, and it alone cannot carry off the heat accumulated by the nuclear fuel during power generation and the heat released in the fuel by nuclear processes after the nuclear chain reaction has stopped. When the loop reactor is shut down, the heat from the coolant of the primary circuit is transferred via metal–metal heat exchangers to the coolant of the secondary circuit, which then dissipates the heat of the shut-down reactor.

The reservoir design makes it possible to have large amounts of sodium at high temperatures and low pressures. Even if the secondary circuit is drained, the active zone avoids accidental overheating after operating at 100% power. The unique experience with the EBR-2 reactor in the United States has fully confirmed this.

Fast-neutron breeder reactors with sodium coolant are technologically superior to thermal-neutron reactors cooled by light water.

Sodium fires can be avoided completely if nitrogen rather than air is present around all components containing liquid sodium. This is expensive, but it completely solves the serious problem of sodium fires.

All over the world there has been a great deal of positive experience with the use of fast-neutron reactors with sodium coolant. Fast-neutron breeder reactors represent the future of large-scale energy production. Currently, there are no fast-neutron reactors anywhere in the world which do not use sodium as the coolant. The creation of fast-neutron breeder reactors which use a coolant other than sodium would require a focused, government-supported program, huge expenditures, and the labor of large, professional groups of researchers for a period of 10–15 years.

On the other hand, in view of the fact that there are no convincing data that it is possible to have maximally safe nuclear energy production based on sodium coolant; and the fact that Britain, the United States, and Germany have practically halted their work on fast-neutron reactors with sodium coolant, while the program in France has also been strongly curtailed; and the fact that work on a construction on a par with the European reactor has been stopped, it is necessary to think and decide, carefully, without bias, and taking into account the views of scientists in France, Britain, and the United states, whether or not it is possible and necessary in Russia to build fast-neutron reactors operating in the closed fuel cycle which use sodium coolant. It should be borne in mind that Russia is the only country in the world which has real theoretical and practical operating experience with nuclear reactors using lead–bismuth coolant, which is considerably more stable in any emergency situation.

Lead–bismuth coolant.

In the Soviet Union, as in the United States, the design of nuclear reactors for submarines took two different paths: water-cooled thermal-neutron reactors and metal-cooled intermediate-neutron reactors.

The American nuclear submarine used sodium coolant, which was a mistake. Small leaks of liquid sodium into the air create a great deal of smoke. Such smoke is very dangerous in a submarine, where people live and work in a small space.

After careful and critical study of sodium, sodium–potassium eutectic, lithium, mercury, lead, and lead–bismuth eutectic as liquid-metal coolants, A. I. Leĭpunskiĭ, the scientific director for nuclear reactors with liquid-metal coolant, chose lead–bismuth eutectic. By this time in the Soviet Union there were laboratory setups using mercury, sodium–potassium eutectic, sodium, and lead-bismuth eutectic.

Lead–bismuth eutectic possesses the following properties:

Its composition is 43.5% Pb+56.5% Bi.
Its melting point is 125 °C.
Its boiling point is 1670 °C.
Its thermal conductivity at 500 °C is 13.9 W/m °C.
Its density at 500 °C is 10 kg/l.
It does not burn in air at working temperatures of 500–600 °C.
It interacts weakly with water.

The physical chemistry and technology of working with the alloy at temperatures of up to 600 °C have been mastered. Construction materials have been selected. It is very unlikely that the eutectic would come to a boil in even the most serious accidents. A reactor using lead–bismuth eutectic can have any neutron spectrum, because the eutectic interacts weakly with neutrons. In large-scale nuclear power production lead–bismuth eutectic can in principle be a universal coolant.

Unique computational, theoretical, experimental, and structural research has been carried out in various institutes of the Soviet Union. Many years of experience have been gained in the operation of laboratory setups, pilot reactors, and real power reactors. The more widespread use of eutectic as a coolant has been hindered by many factors: the common use of water-cooled reactors throughout the world, the lack of nuclear and radiation safeguards during the early stage of nuclear reactor construction, the lack of familiarity with this coolant, the erroneous trust in water as a coolant for nuclear reactors, the example of the United States, creator of the first nuclear weapons and the first nuclear reactors, as a builder of only water-cooled reactors, and the incomplete study during the initial stage of the technology of how to keep the alloy at a given purity.

The construction materials used in the lead–bismuth alloy at working temperatures in the range 300–600 °C lack a shielding oxide film. The solubility of components of the construction materials in the alloy is considerably higher than in liquid sodium at the same temperatures. It was necessary to create a stable acidification of the alloy which would always support the presence of a film on steel and heal exposed areas. The corrosion products and slurry had to be removed from the flux to prevent it from clogging up the passages in the active zone. The oxygen excess threatened to form a large amount of oxides which the traps could not cope with. These accumulate in unreachable locations and clog up the active zone when the thermal and hydraulic regimes are changed, thus creating emergency conditions. All the construction materials tested were able to work more or less safely in a narrow range of stable oxygen content. It was possible to make steel work in the alloy for many thousands of hours. Russian scientists successfully solved this very complicated problem.

Studies were performed on the creation of shielding coverings on steel surfaces which are stable in the lead–bismuth alloy. The light-water coolant did not require such complicated technology and apparatus for withstanding the various conditions. All these factors strongly hindered the broad use of lead–bismuth coolant in nuclear power engineering.

Liquid-metal coolants require completely hermetic circuits in which they circulate. The successful solution of this difficult problem was to some degree aided by the specific thermophysical parameters of liquid metals: the low pressure and high (compared to water coolant) temperature. The melting point of all useful liquid-metal coolants is above 100 °C. All parts of the circulation circuit must be heated, and their temperature must exceed the melting point of the coolant by at least 100 °C. These construction problems were dealt with successfully.

The real drawbacks of lead–bismuth coolant are the following.

(1) The production in neutron fields of bismuth–polonium, which is a dangerous radioactive element:

$$^{209}_{83}\mathrm{Bi}+^{1}_{0}n\rightarrow^{210}_{83}\mathrm{Bi}\rightarrow^{210}_{84}\mathrm{Po}(\beta^-\ \text{decay};\quad \tau_{1/2}=5\ \text{days}),$$

$$^{210}_{84}\mathrm{Po}\rightarrow^{206}_{82}\mathrm{Pb}(\alpha\ \text{decay};\quad \tau_{1/2}=138.4\ \text{days}).$$

The melting point of polonium is 254 °C. Polonium is of greatest danger when it enters the lungs and the digestive tract. The pure α decay of polonium makes shielding easy. The vapor pressure of polonium occurring in the lead–bismuth alloy is considerably lower than in pure polonium. The relatively high melting point 125 °C of the eutectic lead–bismuth alloy means that the polonium-containing alloy solidifies when spilled. Experience has shown that covering a solidified puddle of the alloy with a fairly thin layer of varnish shields the air from the polonium. Rubber gloves shield the skin of the hands.

If necessary, the lead–bismuth alloy can be cleansed of polonium without much effort. The technology exists for removing the polonium and concentrating it in a container.

(2) The high corrosive activity of the lead–bismuth alloy. By now this serious drawback has been fairly well studied, and neutralization methods have been developed. There are ideas about increasing the stability of construction materials in the lead–bismuth alloy at higher temperatures. The search for resistant coverings and more exotic materials which are stable in the alloy at the currently manageable and higher temperatures continues.

(3) The high price of bismuth due to its rarity. However, if the demand for bismuth increases, geologists will find minable deposits.

The exploitation of a liquid-metal coolant does not use it up.

One special feature of all liquid-metal coolants is the possibility of using them over and over. They can be removed from an old reactor, cleaned, and then reused in a new reactor. In view of our experience with building nuclear reactors, it is difficult to imagine that the rate of introducing new reactors will grow to the extent that the availability of bismuth will present a problem.

Lead coolant.

The melting point of lead is 327.4 °C.

The boiling point is 1725 °C.

The density is 11.3 kg/l at 500 °C.

The thermal conductivity at 500 °C is 33.5 W/m °C.

The heat of vaporization is 0.859×10^6 J/l.

The evaporation of one liter of lead or lead–bismuth requires twice as much energy as for one liter of sodium, which is very important in the event of a serious accident. In the 1950s lead was considered for use as a coolant in nuclear reactors for submarines. Since its melting point is higher than that of lead–bismuth eutectic, lead was eliminated from further study.

Its use in fast-neutron reactors—prototypes for large-scale power generation—was not considered, because its thermophysical parameters are inferior to those of sodium.

The interest in lead as a coolant which would ensure safety in nuclear energy production revived in the 1980s, after the accident at Chernobyl.

In mastering lead as a coolant, a great deal can be borrowed from the physical chemistry and technology already worked out for lead–bismuth alloy and sodium. So far there has been no actual experience in using lead as a coolant. Every coolant has its own characteristic features. We need to learn how to use lead coolant as well as we today know how to use lead–bismuth coolant.

Research in the physical chemistry and technology of liquid metals as coolants for nuclear reactors and metal vapors as working objects has been carried out by large groups of professionals for many years now. Sodium, sodium–potassium eutectic, lithium, cesium, potassium, lead–bismuth eutectic, and mercury have all been studied to a greater or lesser degree. The research in this area is a great achievement of Soviet science. For many metals the scientific research was carried out to the construction stage. The reactors functioning in Russia which use liquid-metal coolant were designed directly on the basis of this research. The references to this subject in the international literature are few and laconic. The development of the science and technology of liquid-metal coolants had to be done by ourselves. Of course, not all the research is finished. Much still needs to be done. This research must become one of the principal components of maximally safe nuclear power production.

Currently, Russia has an advantage in the depth and completeness of its knowledge of one of the fundamental components of safe nuclear power production: liquid-metal coolants.

Both Russia and the United States have large arsenals of nuclear weapons. Disarmament, which is impossible without the dismantling of nuclear weaponry, gives rise to the following questions: what should be done with the artificial plutonium removed from nuclear bombs? Can it play a useful role in nuclear power production? Does it need to be stored under observation in special storage facilities? Should it be destroyed, using accelerator technology? Should it be buried forever deep in the Earth? There are just two solutions to the general problem: (1) The plutonium can be used as productively as possible for peaceful purposes, primarily for nuclear power production, and stored until that time, or (2) the plutonium can be annihilated immediately by any method. The plutonium problem is highly politicized. Discussions of it are very often not completely professional; as a rule, it is suggested that Russia unilaterally destroy as much plutonium as possible and as quickly as possible. Plutonium is an alien element in Nature at this epoch. The longest-lived isotope of plutonium is plutonium-244 with a half-life of 8.08×10^7 yr. The half-lives of all plutonium isotopes are much smaller than the age of the Earth. They have all decayed by the present time. Traces of plutonium have been found in uranium ore, owing to spontaneous neutron reactions. In 1940 G. Seaborg obtained the first microgram of plutonium-239, produced artificially from uranium-238.

In all countries possessing nuclear weapons, plutonium-239 was mass-produced using channel-type nuclear reactors burning metallic natural uranium fuel combed into tubes of aluminum alloy. Light water at a temperature of up to 100 °C was used as the coolant, and graphite blocks free from impurities were used as the moderator. Plutonium-239 was radiochemically separated from discharged, highly radioactive blocks of uranium.

It should be remembered that the production of large amounts of plutonium-239 required huge material expenditures and the efforts of the highest-level scientific groups in the land. The destruction of plutonium without making use of it is inadmissible in any situation. Selling plutonium, the starting point of a nuclear weapon, to anyone is criminal.

How can conditioned plutonium be used?

(1) If a developed country possessing nuclear weapons embarked on the intensive construction of nuclear power plants, the plutonium could be used very effectively as the start-up fuel.

(2) It could be used in modern nuclear power production to enrich natural uranium. Uranium–plutonium fuel is used in reactors in the high-burnup regime. Such reactors should be capable of long-term operation, and have low bulk energy release and optimized unit power satisfying the requirements of maximum safety. The plutonium discharged from such reactors is high-background plutonium and not very useful for the mass production of nuclear weapons.

(3) At the present time there is no solution other than storing plutonium in special storage facilities until it is needed for large-scale power production.

Mankind cannot get rid of plutonium once and for all. We have learned to produce it from uranium-238 in nuclear reactors. We have learned to purify plutonium-239 from harmful contaminants by radiochemical methods. We have already built fast-neutron breeder reactors in which with shielding plutonium-239 can be produced from uranium-238 more intensively than in specially designed converters.

In the future, when there are more nuclear power plants than plants burning hydrocarbons, as will certainly happen in all the developed countries by the middle of the twenty-first century, we will have large-scale nuclear power production. It will require a large amount of nuclear fuel. There will not be enough natural uranium-235, and so it will be necessary to switch to uranium–plutonium fuel, and to reuse all the actinides separated from fission products. Uranium–uranium fuel will continue to be used in special-purpose thermal-neutron reactors. The switch to uranium–plutonium fuel will involve the use of the closed fuel cycle with radiochemical processing of the fuel discharged from the reactor.

Modern radiochemistry was developed for separating plutonium from slugs of uranium-238 and plutonium-239 discharged from converters. The main problem was how to better purify the plutonium from fission products. The solution of this problem was one of the great achievements of Soviet radiochemists.

Are the existing methods of separating actinides from fission products optimal for large-scale nuclear power production, when many fast-neutron breeder reactors and reactors with high burnup will be operating? Will it be necessary to develop new radiochemical methods or will modernization of the existing ones suffice? The problems facing the radiochemistry of large-scale nuclear power production are somewhat different from those in the traditional case.

1. The fission products must be thoroughly cleaned of actinoids, rather than the reverse, in order to facilitate the handling and long-term storage or burial of the fission products. It does not matter if a small amount of fission products is present in the uranium–plutonium fuel prepared for a nuclear reactor. The problem is thus the reverse of that encountered in nuclear weapons production.

2. Losses of radioactive products from radiochemical cycles must be minimal or completely absent. After all, it has proved possible to build fast-neutron reactors without losing sodium to the surroundings. Large masses of reprocessed fuel can lead to severe problems if radioactive products are lost. This can give rise to serious obstacles in using nuclear power. Large-scale nuclear power production shifts the rigorous requirements of nuclear and radiation safety not only to the nuclear reactors, but also to the radiochemical processing plants. These plants will bear an increased burden of the radiation safety and also, if violations occur, the nuclear safety.

The closed fuel cycle requires the development of methods for the safe handling, for a time on the order of a century, of fission products and actinides lost through imperfect manufacturing. A sharp distinction should be made between the radiation contamination of the ground and reservoirs in Russia due to justified urgency, lack of experience, and imperfect technology in creating the Soviet nuclear weapons arsenal, and that due to imperfections in the technology of large-scale nuclear power production, which can offer no excuse for producing radiation contamination. It is possible and necessary to develop a safe and low-waste radiochemistry. Large-scale nuclear power generation will not be possible without it.

It will not be possible to switch to nuclear fuel enriched with high-background plutonium without developing robots capable of working in radioactive fields. Robots will be needed for preparing nuclear fuel, fuel elements, and fuel assemblies. The operation of a large number of nuclear reactors, radiochemical plants, and plants working with high-background fuel will make the problem of nuclear and radiation safety acute. The withdrawal from operation of out-of-date or damaged nuclear reactors will lead to the appearance of large amounts of induced radioactivity and poorly cleaned radioactive products. Safe methods will be required for handling these materials and for isolating them from the environment.

Radioactive waste.

There are now many views on how to deal with radioactive waste. Some are already in use, others are under study, and yet others are still only ideas.

The first important question is, where should radioactive waste be stored: above or below ground? If above, observation and evacuation, if necessary, must be possible. Such storage facilities must be carefully maintained for many years. If the waste is stored below ground, it would stay forever, without any possibility of being unearthed. Are there guarantees that human and natural catastrophes cannot violate the hermeticity of such underground storage facilities? If violation of hermeticity did occur, what would happen in view of the fact that there are no chemical methods for eliminating radioactivity? Are there any chemical compounds soluble or insoluble in water which are more or less stable to the emission of radiation by radioactive waste?

The second question is, should radioactive waste be stored in the form of a solution or as a solid? Some countries mix radioactive waste with cement, glass, or organic material to harden it, place it in stainless steel tanks, and dump it into the ocean.

In the Soviet Union, liquid radioactive wastes containing not only fission products but also actinides were stored in geological formations with fresh water. Geologists think that the hermeticity of these formations cannot be violated. It should be remembered that the half-lives of actinides are thousands of years, and that they are not only radioactive, but also poisonous to anything alive.

At one time it was recommended that radioactive wastes be placed in vats and stored in sodium-chloride mines. This was rejected because of the corrosive action of chlorine.

It is possible to dilute radioactive isotopes in large masses of water to safe concentrations. However, this is inadmissible, because there are processes and organisms in nature which can reconcentrate the dilute material.

The crucial question arises of destroying radioactive waste by using neutron reactions. For example, it has now become clear that all actinides, including neptunium, americium, and curium can be burned up in nuclear reactors. Thermonuclear neutrons may be useful for this. The main problem is not losing actinides in the closed fuel cycle. The transmutation of strontium, cesium, and carbon-14 has proved impossible.

Recent advances by Russian scientists working in accelerator and nuclear physics create optimism about the possibility of the complete destruction of americium, curium, and neptunium, and also fission products possessing small cross sections at the neutron energies available in fission and fusion reactors.

A very important problem for large-scale nuclear power production, which in the future will also involve thermonuclear reactors, is the tritium problem.

Tritium is discharged into the environment in the operation of nuclear power plants and radiochemical processing plants.

Tritium is produced in actinide fission. One out of every ten thousand fission events is a triple fission producing tritium. For example, in one year of operation of a nuclear power plant producing a unit power of 1 GW, where about a thousand kilograms of actinides are burned, about 1.25 grams of tritium are produced, which is not very much.

In sodium coolant tritium is produced from lithium, trace amounts of which always occur in sodium. This lithium is completely burned up over time.

Tritium is produced from boron, which is widely used as an absorber. It is also used in the form of metal control rods in all nuclear devices and as a liquid solution in water-cooled reactors (the borating of water).

In water, tritium forms superheavy water and enters the environment when water is lost from the primary circuit.

In reactors with liquid-metal coolant, gaseous tritium can diffuse through the hot walls into the surroundings.

Tritium is the nuclear fuel in thermonuclear reactors. Tritium is the fuel of thermonuclear fusion. The problem of tritium loss arises in the production and storage of tritium, in the target preparation, and when tritium is fed into the toroid of a thermonuclear reactor with magnetic plasma confinement. The losses in thermonuclear reactions occur primarily as a result of diffusion through the first wall. In order to obtain a license for operating a thermonuclear power reactor, it will be necessary to show that the tritium problem has been solved.

At present, radioactive water vapor containing tritium and the noble gas krypton from nonhermetic fuel elements is dumped into the ventilating tubing of the nuclear reactor. As long as the admixtures of these gases are small, they do not affect the atmosphere. Obviously, if they become large and have a serious ionizing effect on the atmosphere, they must be contained.

All the problems of radiation safety that we have listed have a solution. There are no fundamental difficulties which make it impossible to have nuclear power production without radiation effects on the environment.

There are scientific foundations for developing maximally safe nuclear energy production which does not threaten people with either nuclear or radiation catastrophes.

Maximally safe nuclear power reactors.

1. Helium–graphite reactors. These reactors are characterized by the use of core nuclear fuel, optimized unit power, and moderate bulk energy output.

In the event of a complete loss of the helium, these reactors are self-quenching, owing to a unique property of graphite: its sublimation point is 4000 °C. Its thermal conductivity is the same as for metals. It has a large heat capacity at high temperatures, and large masses of graphite allow the accumulation of a large amount of energy without structural damage. The nuclear chain reaction stops when the temperature becomes too high. The residual heat release is dumped into the surroundings via the exterior surface. The system comes into equilibrium.

The core fuel and the graphite matrix must support the bulk of the fission products and actinides. The helium is not activated, and will contain trace concentrations of gaseous fission products and dust with induced radioactivity. Loss of helium to the surroundings must not lead to severe radiation contamination. Shielding should be used to prevent the oxygen of air from coming into contact with the heated graphite in the event of an accidental opening through which the helium coolant could leave the active zone.

2. Lead–bismuth coolant. This provides optimized unit power and moderate bulk energy output. The temperature of the alloy at the exit from the active zone can reach 600 °C. There is a reservoir arrangement. The reservoir has double walls separated by a space. An accidental leak of the alloy into the space does not lead to uncovering of the active zone. In the event of an accident involving a steam generator, steam cannot enter the active zone. There can be any neutron spectrum. The breeding ratio varies from greater than one to less than one.

3. Lead–bismuth coolant. Heavy-water moderator. This provides optimized unit power and moderate bulk energy output. The temperature of the alloy at the exit from the active zone can reach 500 °C. There is a reservoir–channel arrangement. The nuclear chain reaction is quenched when the heavy water is drained off. The lead–bismuth alloy cannot escape from the active zone and removes the residual heat output.

4. Lead coolant. If the risk associated with polonium and the insufficient supply of bismuth are important considerations, lead without bismuth can be used as the coolant. According to most physico-chemical and technological studies, lead is inferior to the alloy. A complete series of studies should be carried out to learn about the use of lead as a coolant.

5. Salt-based homogeneous reactors. ($^7LiF, BeF_2, UF_4, ThF_4$) Liquid-salt nuclear reactors achieve minimal reactivity margin, owing to the possibility of the regulated, continuous input of the nuclear fuel and raw fuel. Salt reactors possess instantaneous negative temperature reactivity coefficient, which ensures self-regulation of the reactor in temperature. In homogeneous nuclear reactors the fuel is not at a high temperature relative to the coolant. The homogeneous design has the great advantage that it does not require the large-scale manufacture of fuel elements (for large-scale power production) from high-background nuclear fuel. All serious accidents at nuclear reactors due to problems with the fuel elements are avoided, but the homogeneous nuclear reactor lacks two barriers for containing the fission products and radioactive actinides: the solid fuel and the metal casing of the fuel elements.

Liquid-salt nuclear reactors possess a high degree of nuclear safety and an extremely high degree of radiation safety. It is not yet known whether constructive solutions to the above problem can be found. The other main unsolved problems of these reactors are the radiolysis and pyrolysis occurring in salts, and the physico-chemical processes occurring in salts which lead to the appearance of a large amount of decay products and artificial actinides. There is the possibility that sediments of actinide-containing compounds can be deposited in long-term operation. The behavior of graphite corrosion and erosion products and the construction materials of the heat exchangers, the reactor housing, and the pumps in the salt environment is not known.

In salts, tritium is produced from lithium-7 and beryllium-9, and also in the triple fission of the nuclear fuel. The tritium problem is further complicated by the fact that tritium does not form chemical compounds inside the reactor and is present in gaseous form. All the subassemblies of the active zone of a homogeneous reactor are at a temperature of about 600 °C, and the tritium easily diffuses through the metal walls into the surroundings.

Nuclear reactions of actinides and also of lithium and beryllium liberate atomic fluorine. How will fluorine behave at the high temperatures and in the large concentrations produced during long-term operation? Will it interact with the construction materials and form chemical compounds with fission products?

In spite of the useful features of a homogeneous reactor compared to a heterogeneous one, until the problems listed above are solved, it is premature to build a salt reactor. Fundamental theoretical, computational, and experimental feasibility studies must be performed.

Fission reactors with preliminary neutron irradiation

The interest in the idea of a reactor based on the fission of heavy nuclei with preliminary neutron irradiation has been revisited many times. The main drawback has been the lack of accelerators and high-power lasers able to operate in the power-production mode instead of at just the scale of laboratory research.

Preliminary neutron irradiation is possible on the basis of the following principles:

(a) The pulsed fission reactor. Here the active zone of the reactor is divided into two parts: a stationary part which is subcritical, and a mobile part which is also subcritical. Supercriticality arises when the mobile part of the active zone is introduced into the stationary part. The nuclear reactor can operate in the subcritical and the supercritical regimes. The cooling of the mobile part of the active zone and the operation of the fuel elements in the pulsed mode are serious problems.

Such a reactor does not require new, complicated technology, because it was the first of a series of reactors with preliminary neutron irradiation built in the 1960s in the Soviet Union.

That reactor was a research (not a power) reactor. The energy released in nuclear bursts was absorbed by the heat capacity of the reactor and dissipated into the surroundings. The cooling time of the reactor was limited by the frequency of the nuclear bursts. The energy source was the fission of heavy nuclei in the pulsed mode.

(b) Preliminary irradiation by neutrons obtained by the accelerator technique. An accelerator can be used to obtain a neutron flux from the charge exchange of ions accelerated in an accelerator. Preliminary irradiation of a subcritical assembly by a neutron flux fully guarantees nuclear safety, independent of operator error and sabotage. A nuclear burst in the active zone which could lead to a crisis is completely impossible. A nuclear reactor of this type with guaranteed energy withdrawal in any operating regime producing nuclear power satisfies the most rigorous safety requirements.

Preliminary irradiation by neutrons from an external source is useful if it ensures sufficient subcriticality. This means that the irradiation must transfer a large amount of energy to the active zone from a neutron source independent of the fission of actinide nuclei. About 30% of the ion beam energy will be transformed into electrical energy via the heat cycle of the nuclear reactor. Subcriticality of the active zone will either decrease or increase this, depending on the type of reactor. This will determine the duration of continuous operation. By changing the irradiation energy it is possible to regulate the power of the nuclear reactor and compensate for a change of subcriticality, i.e., the energy output of the entire reactor is regulated by the ion accelerator. It is no longer necessary to have a quick-response emergency shielding system in the active zone.

The accelerator must possess absolutely reliable means of limiting the energy transferred to the ion flux.

A nuclear reactor of this type has no need of a reactivity margin, i.e., an absorber of excess neutrons. More rational use is made of the nuclear fuel in the subcritical assembly.

Obviously, great difficulties will be encountered in constructing the target, in which the high-energy ions obtained in the accelerator must undergo charge-exchange reactions to produce neutrons. The energy transferred from the ions to the neutrons is in the megawatt range. The energy transformed into heat in the charge exchange must be removed. The target, which is smaller than the reactor, is also an energy-producing object. Of what material should the target be made? Should it be a solid or a liquid? What about loss of the target mass, activation of the target, and the "lifetime"? What about discharging the spent target?

Is it realistic to build a single 100–200 MW accelerator, or should accelerators of lower power be built?

The creation of a working active actinide-fission zone of practically any low power makes it possible, before building a full-scale power reactor, to construct a low-power model reactor which can be used to verify, under realistic conditions, all the basic principles of the design and to introduce corrections.

A multi-module version of a power reactor is possible. The active zone can be designed to produce any power from kilowatts to gigawatts. An optimized accelerator is designed, and a subcritical active zone is created for it.

The optimal unit power of a nuclear reactor has not been seriously studied in modern nuclear power engineering. The striving to increase the unit power is dictated only by technical and economical considerations, without considering the effect of the unit power, i.e., the amount of enriched nuclear fuel burned in the reactor, on nuclear safety, the tendency for accidents to occur, or the scale of the radiation releases when an accident does occur. Some reactor builders think that it is more advantageous to obtain any required amount of power from nuclear reactors of intermediate power assembled at the manufacturing site, rather than at the installation site.

At present, all the fundamental problems associated with the nuclear processes occurring in the active zone using irradiation by an ion flux obtained from an accelerator are not really known. The construction of such a hybrid setup is premature. Fundamental theoretical, computational, and experimental studies must be carried out. Such a hybrid nuclear reactor makes sense only if it ensures a degree of nuclear safety higher than that of the maximally safe nuclear reactors of the future which do not use preliminary neutron irradiation or which use preliminary irradiation obtained on the basis of other principles.

When an accelerator is used for preliminary neutron irradiation, there is only one energy source: the fission of heavy nuclei. Part of the electrical energy produced in such a reactor must go, in the form of electric current, to operate the accelerator. Obviously, the total efficiency of such a hybrid setup will not be high. If such a hybrid reactor ensures maximum safety, we will be forced to resign ourselves to the fact that safety must be paid for.

(c) Preliminary irradiation by neutrons obtained in a thermonuclear device with inertial plasma confinement. The energy obtained in actinide fission corresponds to 2.5% in the form of fast neutrons and 83.5% in the form of kinetic energy of the fission products.

The energy obtained in deuterium–tritium fusion corresponds to 80% in the form of 14-MeV neutrons and 20% in the form of 3.5-MeV α particles.

Most of the energy in the fission of heavy nuclei is in the heavy decay products, which are located in the nuclear fuel and which in the normal operating mode of a power reactor do not leave it, but heat up all the nuclear fuel. In the fusion of light nuclei, most of the energy is in the fast neutrons, and less is in the helium nuclei. Both the neutrons and the helium nuclei leave the fusion site. The flux of thermonuclear neutrons, i.e., most of the energy from the fusion reaction, can be used far from where it originates.

There are two sources of energy in preliminary irradiation by thermonuclear neutrons: thermonuclear fusion and the fission of heavy nuclei. The fraction of each can vary within a fairly wide range, depending on advances in thermonuclear fusion. Thermonuclear fusion with inertial plasma confinement requires (in the variant being studied now) electrical energy to power the laser beam. The thermonuclear part of the nuclear power reactor must operate continuously for a specified time with continuous output of electrical energy.

Inertial plasma confinement—compression of the target by beams—makes it possible in principle to solve the problem of the first wall. The site of the target explosion (inside the detonation chamber) can be surrounded by streams of liquid or solid materials from uranium-238 for making plutonium-239, lithium for making tritium, and other inert materials. The created neutrons do not need to be sent through the wall to a blanket for neutron reactions.

Thermonuclear reactions based on deuterium–tritium fusion must be safe as regards tritium.

Hybrid nuclear power reactors should equal and even surpass, primarily in nuclear safety, existing reactors based on actinide fission, and be able to compete with the promising fission-based nuclear reactors of the future.

Hybrid nuclear reactors with preliminary neutron irradiation using an accelerator or a laser allow the mechanical control of the nuclear chain reaction to be replaced by purely electrical control.

In order for reactors based on the fission of heavy nuclei with heterogeneous activity zone to have a sufficiently long operating time, more fissile material than needed to start the nuclear reaction is introduced initially into the active zone. The neutron excess is absorbed by either solid or liquid neutron absorbers. These absorbers regulate the energy given off by the nuclear processes.

Boron is used most often as an absorber. Natural boron consists of two isotopes, ^{10}B (18.7%) and ^{11}B (81.3%). The nuclear reactions $^{11}\mathrm{B}+n\rightarrow{}^{3}\mathrm{T}+{}^{9}\mathrm{Be}$ and $^{10}\mathrm{B}+n\rightarrow{}^{3}\mathrm{T}+2\,{}^{4}\mathrm{He}$ occur in neutron fields.

Either solid or liquid absorbers are introduced into the active zone for emergency stopping. This insertion is done mechanically. In principle, there is no guarantee that the insertion mechanism will work, that the absorber rods will not jam, or that they will fill the entire active zone quickly enough. The same is true of liquid absorbers used in water–water reactors. Owing to nuclear processes, the energy released in the absorber rods is several times smaller than that in the fuel elements. This energy is removed by the coolant. Ineffective cooling can lead to overheating and deformation of the rods. It is also impossible in principle to exclude the possibility that the absorber rods cannot be removed from the active zone, which would lead to a very serious situation: reactor runaway.

The raw nuclear fuel in a reactor with preliminary neutron irradiation can be either natural uranium or thorium. Should the natural fuel be enriched, or is this not necessary?

The preliminary irradiation can be performed by using a neutron flux of any energy if an ion accelerator is used.

Will the composition of the fission products differ from that of the fission products of an ordinary reactor? Can the energy of the neutrons in the preliminary irradiation affect the radioactivity of the spent fuel? Isn't it possible to burn up at least some of the radioactive isotopes accumulated in nuclear power production in zones with preliminary irradiation?

For large-scale nuclear power production with the closed fuel cycle, which nuclear raw material, natural uranium or thorium, is more advantageous from the viewpoint of the radiochemical processing of the spent fuel?

What burnup fraction can be attained in a reactor with preliminary irradiation? Is it possible to obtain more complete burnup than in currently operating reactors and thereby make radiochemical reprocessing unnecessary in large-scale power production? What composition of the fuel after radiochemical reprocessing is most suitable for a reactor with preliminary irradiation?

Preliminary irradiation must ensure compensation for the change of reactivity of the active zone over a sufficiently long period of time in order that it not be necessary to reload the fuel in the active zone too often. In what range of reactivity can complete reactivity safety be ensured?

The accelerator is completely capable of regulating the power and stopping the nuclear chain reaction in an emergency, and also guaranteeing that runaway of the reactor cannot occur. There is no need for the active zone to contain power-regulating rods or emergency shielding rods when preliminary neutron irradiation is used.

The speed with which electrical disconnection of the accelerator affects the neutron processes is much greater than that of any of the fastest mechanisms for stopping the nuclear chain reaction by introducing neutron absorbers into the active zone.

What neutron energy is optimal in preliminary neutron irradiation? The important requirement which must be satisfied in optimizing the energy of these neutrons and the fraction of these neutrons involved in the nuclear chain reaction is the requirement of maximal nuclear safety. It is necessary to take into account how the energy of these neutrons affects the isotope content of the fission products and actinides. The economics of the accelerator and charge-exchange setup must be evaluated in choosing this neutron energy. Accidents at the accelerator and the charge-exchange setup must in no situation lead to an accident in the active zone. Each component of the raw nuclear fuel will undergo fission directly, owing to neutrons of the preliminary irradiation. How do the processes of a branched chain reaction proceed? Is it possible to lose control?

When lead–bismuth eutectic or pure lead is used as the coolant in the active zone of an electronuclear reactor, it will be possible to have the ion charge exchange occur in the active zone itself. In this case, over the mirror of the coolant in the active zone it will be necessary to have not inert gas, but a vacuum. The high boiling point of the eutectic, ≈ 1670 °C, makes it possible to have a small density of lead and bismuth vapor in the vacuum at coolant working temperatures of 500–550 °C.

It can be expected that a nuclear reactor with preliminary neutron irradiation and guaranteed withdrawal of the energy released in any situation will be the safest of all nuclear reactors of the future.

Control of the energy produced in a fission reactor with preliminary neutron irradiation by regulating the ion beam energy allows the more economical use of nuclear fuel.

Greater economy also results from the use in the heat cycle of the thermal energy generated in the target by ion charge-exchange reactions.

Liquid-metal cooling of the nuclear reactor makes it possible to have quite good thermodynamical parameters for the transformation of thermal energy into electrical energy.

All these factors ensure that a nuclear reactor with preliminary neutron irradiation will have an acceptable efficiency.

Accelerators which operate reliably in the power mode can be used for the transmutation of radioactive waste, and also to study the possibility of using a high-energy ion beam for thermonuclear fusion with inertial confinement.

Transmutation.

The high toxicity and long-lived radioactivity of artificial actinides and fission products of heavy nuclei make the problem of radioactive waste extremely important.

The artificial actinides produced in the active zone of a nuclear reactor based on nuclide fission are:

^{241}Am, $\tau_{1/2}=432.2$ yr,

^{243}Am, $\tau_{1/2}=7380$ yr,

^{242}Cm, $\tau_{1/2}=162.8$ days,

^{244}Cm, $\tau_{1/2}=18.1$ yr,

^{237}Np, $\tau_{1/2}=2.14\times10^6$ yr.

Actinides occurring in small amounts can be burned in fast-neutron reactors, or imbedded in uranium–plutonium fuel in strictly controlled amounts, or burned up in a special-purpose reactor for burning small amounts of actinides.

Thermal-neutron reactors cannot destroy small amounts of actinides. Actinides accumulate in the active zone of these reactors.

Fast-neutron reactors can only decrease the amount of small quantities of actinides; they cannot destroy them completely, because they are continually being produced in the nuclear fuel. Artificial actinides can be destroyed completely by bombarding them with neutrons obtained from sources unrelated to the fission of heavy nuclei. Thermonuclear neutrons and an ion flux from an accelerator can cleanse the fuel cycle of an excess of artificial actinides.

The radioactive nuclides of the fission products are not all equally dangerous radiologically. Nuclides forming monovalent ions are soluble in water and can be ejected into the biosphere along with the water. The particularly dangerous fission products are

$^{90}_{38}$Sr, $\tau_{1/2}=28.6$ yr, the analog of calcium, and

$^{137}_{55}$Cs, $\tau_{1/2}=30.0$ yr, the analog of potassium.

Accelerator technology can already be used to obtain ions with an energy of several GeV. It is hoped that high-energy ions will be able to transmute strontium and cesium. There are indications that high-energy particles can destroy nuclei with the release of a large number of neutrons and protons. It would be nice to be able to use the neutrons arising in the transmutation process. Transmutation works if radioactive isotopes are either completely annihilated owing to complete destruction of their nuclei or reduced to short- or long-lived isotopes.

Industrial transmutation requires the mass production of targets. Targets are highly radioactive. They must obviously possess a system to remove the heat given off by the reactions. Depending on progress in radiochemistry, targets of strontium and cesium will have different admixtures of actinides and fission products. The tolerances in the target mass, geometrical parameters, and impurities in the irradiated chemical element must be worked out. In what state is it most convenient to have the irradiated material, solid, liquid, gas, or emulsion?

The tolerances for actinides in targets can indirectly affect the radiochemical processing of spent reactor fuel.

For preliminary irradiation of the nuclear reactor and transmutation, the targets prepared using construction materials will have a high induced radioactivity. Methods of discharging, transporting, and storing these highly radioactive compounds must be developed. However, their ecological danger is considerably milder than that of transuranium elements, fission products, tritium, and carbon-14.

Large-scale nuclear power production requires a technical and economic comparison of transmutation and guaranteed storage (burial) of radioactive strontium and cesium for 300 years and the possibilities offered by other methods of localization and destruction. It should be borne in mind that transmutation guarantees the complete destruction of the radioactive waste from nuclear power production. Storage or burial for 300 years cannot give any such guarantee.

The creation of targets from radioactive elements, like the radiochemical preparation of radioactive waste for long-term storage or burial, involves working with high levels of radioactivity.

A great deal of positive experience has been gained in the use of nuclear power setups designed for a variety of purposes. However, there have been accidents at Chernobyl and Three-Mile Island, and accidents in nuclear submarines. The situation must be soberly reviewed. It is dangerous to maintain that everything is fine, that we understand what happened and why, that it will never happen again, that the existing nuclear power plants are outdated. We will just pursue the path of gradual improvement, not making any fundamental changes, as after all the principles and methods of enhancing the safety of nuclear power plants have already come a long way. On the other hand, it is impossible to panic and demand that all nuclear power plants be closed.

Maximally safe nuclear power production guarantees that the worldwide need for electricity and heat on any scale will be satisfied for an infinitely long time.

The abundance of accumulated nuclear fuel, uranium-235 and plutonium-239, in Russia makes nuclear power production stable at the present time.

Russia sells a large amount of natural gas abroad. Natural gas cannot be a global energy source for a long time. In Russia it can be the main source of energy for another 15–20 years. During this time we can develop maximally safe nuclear power production and ecologically sound energy production based on coal.

The unavoidability of the widespread use of nuclear energy in Russia in the twenty-first century is dictated by the specific features of our country. Practically all the useful mineral and large hydrocarbon deposits are located in sparsely populated areas in the East and North which have a severe climate. Most of the population and the overwhelming majority of the industry are located in the West, where there are few sources of energy. Large amounts of oil and gas are transported over pipelines from the East to the West. The transport of large amounts of coal, the principal hydrocarbon fuel of the twenty-first century, from the East is very problematical. There are many difficulties associated with the construction of electric power plants at the site where the coal is mined and then transferring large amounts of electricity to the European part of Russia. In spite of the unique reserves of hydrocarbon fuel in Russia, it is more reasonable to rely on nuclear energy in the West and the Far East. The heat content of nuclear fuel, which is a million times that of organic fuel, eliminates the problem of transporting it over very large distances.

The global requirement on energy sources has increased by about a factor of 20 since the beginning of the twentieth century. The amount of raw material used throughout the world in the second half of the twentieth century is equal to that used in the entire preceding history of mankind.

A number of world conferences have been held in the 1990s to discuss the following problems: world population growth; the nonuniform increase in population in different continents and countries (the high growth rate in poor and developing countries); ways of ensuring that people in poor countries have adequate food supplies. Attention has been drawn to the fact that mankind is approaching a critical point with regard to the problems of world population and protection of the environment.

The world population is continuously increasing. Is it possible to control and regulate population growth to the minimum survival rate without wars, epidemics, and hunger, and, instead, by means of laws freely accepted by human society, or is this impossible in principle? What will be the consequences for human society? The demographic problem is obviously more important, more global, than any other problem facing mankind today. The industrially developed countries consume 70% of the meat and milk, 75% of the energy, and 80% of the iron and steel.

The population of the United States makes up $\approx 5\%$ of the world population. Each inhabitant of the United States uses 5 times more energy than the average amount of energy available to everyone on the planet.

In the 1980s in the United States each inhabitant consumed ≈ 11 tons of conventional fuel or $\approx 3.2\times10^{11}$ J/yr or ≈ 10 kW/person. This energy is obtained from oil produced domestically and purchased from abroad, natural gas, coal, nuclear energy, and water power.

If we assume that 20% of the world population, i.e., 1.3×10^9 people, live in developed countries, and that each person uses 8.0 tcf (tons of conventional fuel), then, owing to energy-conserving technologies and the shift of many energy-consuming industries to developing countries, the energy sources required will not exceed $\approx 10.4\times10^9$ tcf. In developing countries, where 80% of the world's population, i.e., 5.3×10^9 people, live, and where the birth rate is high, the requirement of 3.0 tcf per person per year gives 15.9 $\times10^9$ tcf per year. Altogether, the population of 6.6×10^9 will require 26.3×10^9 tcf. There is no guarantee that the population at the beginning of the twenty-first century will not exceed 6.6×10^9. At the end of the twentieth century the world output of energy sources is $\approx 15\times10^9$ tcf. What should we do? Condemn part of the world to poverty?

Focusing on the output of hydrocarbon fuel is unrealistic, because the main bet in developing countries should be made on nuclear energy.

Even with the science and technology most favorable for their development, hydrocarbon energy sources cannot ensure the growing population of the world the amount of energy needed even for minimal use. Only maximally safe nuclear power production based on the fission of heavy nuclei and the fusion of light nuclei can in principle satisfy any of mankind's requirements for electricity and fresh water. Only nuclear power can alleviate the crisis developing because of the growth of the world's population.

Discussions about whether or not nuclear energy is needed are senseless. If we strip away the illusions and look several decades ahead, it becomes clear that we cannot do without nuclear energy, whether we like it or not. There is only one way forward: the rapid and competent development of nuclear power production which is maximally safe in all its aspects, with special attention paid to radiation safety.

A much more important question facing mankind which has arisen only recently in human existence is that of uncontrolled population growth, which can lead to extinction of the human species.

Ensuring the population of Russia, which will be 200×10^6 at the beginning of the twenty-first century, with energy at a level of 11 tcf per person will require 3.2×10^{11} J/yr. This means a total of 2.2×10^9 tcf or 6.4×10^{19} J. In 1977 the Soviet Union consumed 950×10^6 tcf of oil, 870×10^6 tcf of natural gas, and 470×10^6 tcf of coal, i.e., a total of 2.29×10^9 tcf. A quite realistic requirement in Russia at the beginning of the twenty-first century will be 1.8×10^9 tcf or 5.3×10^{19} J/yr of hydrocarbon fuel and 1.1×10^{19} J/yr of nuclear energy, i.e., it will be necessary to have nuclear energy with a unit power of 350 GW. It should be possible to manage this in 25 years.

People need reliable sources of a sufficient quantity of energy to live a comfortable life. Just how this energy is obtained is of no particular concern to them.

Science and technology have created such sources, which even in emergency situations have not unduly frightened people or had an adverse effect on their health or threatened their lives.

In this study I have tried to stress the following points:

In the twenty-first century mankind cannot do without economical nuclear power which is maximally safe in all its aspects.

The existing water-cooled nuclear reactors cannot burn all the uranium-238, and water, owing to its physicochemical properties, cannot ensure that a nuclear reactor is safe.

It is possible to develop maximally safe nuclear power production on the basis of various well-founded physical principles.

There may be ideas other than those discussed here for ensuring maximally safe nuclear power production.

It would be good if the countries engaged in building nuclear reactors proceeded in one or two directions, and constructed pilot plants in complete openness while keeping in contact with outsiders.

Advances in accelerator science and technology raise hopes that it will be possible to transmute radioactive nuclear waste and highly radioactive transuranium elements.

The most elegant engineering solutions for an unsatisfactory physics cannot ensure the creation of maximally safe nuclear power production.

The main criterion which a nuclear power plant should satisfy is the possibility of self-quenching (on the basis of physical principles) in situations which deviate from the normal.

The high scientific level and accumulated experience of the countries which are building nuclear power reactors for various purposes ensure the possibility of developing nuclear power production which is maximally safe in all its aspects when the governments in question are supportive of this extremely important goal.

The ideas discussed here have been discussed repeatedly with A. I. Leĭpunskiĭ, A. P. Aleksandrov, A. M. Baldin, N. G. Basov, V. A. Kirillin, G. I. Marchuk, M. V. Maslennikov, V. I. Matveev, V. V. Orlov, L. P. Feoktistov, A. E. Sheĭndlin, S. B. Shikhov, and G. N. Yakovlev.

*This article reflects the personal views of Academician V. I. Subbotin, a well-known expert on nuclear reactors, about the problems of modern nuclear power.—Editorial office, Fiz. Élem. Chastits At. Yadra.

Translated by Patricia A. Millard from the original manuscripts as submitted by the Author. The published Russian version of this paper was heavily edited by the journal Editorial office, and, therefore, it significantly differs from its English translation.