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PROBLEMS OF NUCLEAR POWER ENGINEERING: HISTORY AND PRESENT

1. Introduction

The work contains seven sections and four appendices. All sections deal with various aspects of nuclear power engineering. The appendices are devoted to the issues of nuclear power engineering and its history, in particular, the confrontation between the USA and the USSR (Russia) on the sea and in space. We attract attention to Appendix 1 "Nuclear accidents". The IAEA materials were used to analyze the origin of each accident. The result turned out to be unexpected: the number of accidents because of personnel mistakes is approximately twice as large as because of technical malfunctions.

The structure of the work is as follows. In Section 2, the correlation between the amount of energy produced per capita and the average lifespan is analyzed for various countries with different cultures. A conclusion is drawn that the lifespan undoubtedly depends on the energy produced per capita. This means that the power capacities will be increased in the third-world and developing countries. For example, the People's Republic of China announced about the increase of energy sources by several tens of times owing to the construction of new nuclear power plants.

In Section 3, the issue of Earth's climate change is discussed. The relevant data of observations over a large time period are presented, which demonstrate that the average Earth temperature grows. This growth is shown to correlate with the increase in the amount of carbon dioxide in the atmosphere (the greenhouse effect). The role of modern CO_2 sources in the household and communal service domains, industry, and transport is analyzed. The problem of energy sources that could satisfy mankind's requirements for energy without climate deterioration is discussed. The development of nuclear power engineering is shown to be the most comprehensible way to increase the power of energy sources. Taking into account that approximately one seventh of Earth's population (1 billion) starves at present, the use of lands to cultivate crops as energy resources is an expensive way.

It is known that the development of works on nuclear power engineering initially had purely military purposes. Two atomic projects, American and Soviet, were developed the most successively. Within 1942–1945, American scientists and engineers managed to solve the most complicated technical and scientific problems and to master the nuclear energy in the form of atomic bombs. The American atomic project was called "The Manhattan project". It was stimulated by the danger of the creation of an atomic bomb in Germany. By the middle of 1945, the American government had three atomic bombs. One of them was exploded experimentally; the two others were dropped on Hiroshima and Nagasaki.

The Soviet atomic project was started in 1945. A large role in the realizations of this project was played by the Soviet intelligence service and the scientist Klaus Fuchs. Klaus Fuchs decided to transfer the know-how of the atomic bomb production to the Soviet Union, proceeding from his comprehension of the important role of the Soviet Union in the defeat of Germany and the losses suffered by the Soviet Union in the World War II. Soviet scientists successively overcame large difficulties, whereas the government provided required materials and the intellectual basis. The production of explosives – namely, uranium-235 and plutonium-239 – constituted the basic difficulty. The USSR tested its first atomic bomb on August 29, 1949. The creation of thermonuclear weapons was the next large stage in both the Soviet and American atomic projects. Those events are discussed in Section 4.

Sections 5 and 6 are devoted to the analysis of possibilities of modern nuclear power engineering. Its advantages and shortcomings are considered in detail. One of the tasks is the creation of physically safe reactor. Hopes for the solution of this problem have appeared after Feoktistov's project. American (Teller and his disciples) and Japanese scientists came to the idea of safe nuclear reactor independently. However, this problem has not been solved yet, and large efforts will be required for its solution.

It is well known that a special attention is paid to the physical, moral, and educational levels of executors in expensive industries (e.g., space industry). In the nuclear power engineering, which is undoubtedly an expensive kind of industry, requirements still remain confined to the educational level. After the Chernobyl disaster, there emerged a movement on the culture of safety in nuclear power engineering. In Section 7, issues concerning the improving of safety at nuclear power plant by paying a more attention to the personnel are discussed in the framework of a scientific approach.

2. Energy Production and Living Standard

Nowadays, the issues of nuclear power engineering become of special importance. It will be recalled that, at present, about 440 nuclear reactors are exploited at about 200 nuclear power plants in 30 countries over the world. Their total electric power is about 370,000 MW [1,2]. The United States is a world leader in the electric power production at nuclear reactors. More than 100 blocks at 63 nuclear power plants are exploited in this country, and about 20% of the total electric power is generated with their help. Note also that 19 nuclear power plants (58 blocks) produce about 75% of electric power in France.

Table 1. **World's energy consumption in various economic sectors [3, 4]**

	Year			
	2000	2008	2000	2008
	10^{12} Wh		%	
Industry	21.733	27.273	26.5	27.8
Transport	22.563	26.742	27.5	27.3
Private consumption and services	30.555	35.319	37.3	36.0
Others	7.119	8.688	8.7	8.9
Total	81.970	98.022	100	100

Nuclear reactors do not consume oxygen from the atmosphere in principle, unlike thermal power stations and heat and power plants, which generate the dominating part of energy in the world (see Table 1).

Nuclear power engineering is a sector of the economy that includes the study and the application of the energy that is contained in atomic nuclei, in particular, uranium-235, plutonium-239, and MOX fuel (the mixture of uranium and plutonium oxides). The development of nuclear power engineering is always accompanied by a discussion concerning its necessity and possible danger.

In this paper, we present our considerations on the necessity of nuclear power engineering, the adoption of accident control measures to eliminate its danger, and discuss some promising directions for the development of nuclear power engineering in the 21st century, including the creation of physically safe nuclear reactor. In our work, we widely used the data provided by the IAEA and the UN organization.

It is well known that, in order to maintain a high living standard for people, a definite amount of energy per capita has to be produced. Today, all the countries throughout the world can be conditionally divided into three groups. The first group includes the countries of Western Europe and North America, Japan, and Australia. The living standard in those countries is high enough, if to judge by the average lifespan in them. Table 2 contains data on the energy production per capita, average lifespan, and total energy production in various countries.

The second group includes countries with a developing economy. Among them, there are China, India, Pakistan, Brazil, Russia, and Ukraine. The average lifespan in those countries, as well as the energy production, is shorter than that in the first group. In particular, in Russia in 2012, the average lifespan was 64 years for men and 76 years for women, and the energy production amounted to 6300 kWh/person. In

Ukraine, the corresponding numbers equaled 62 years for men, 73 years for women, and 4200 kWh/person for energy production. The difference between the lifespans of men and women in Russia and Ukraine is associated with their lifestyle.

A large number of African countries are classed to the third group. In those countries, the demands for ordered energy sources are some lower, because those counties are located in a region with a warm climate. The average lifespan in Africa is 49 years for men and 52 years for women. The energy production per capita in Africa was equal to 267 kWh/person in 2009, which is approximately several hundred times lower than in Europe.

3. Change of the Earth's Climate and Power Engineering Capabilities

Let us recall that about 5 bln of Earth's 7-bln population now live in countries belonging to the second and third groups. Approximately 1 billion people of the population in those countries starve. Therefore, it is clear that the produced energy amount has to grow in the near future by approximately a factor of 2 to 3.

It is well known that the energy is generated at present owing to the chemical reaction of coal, oil, or gas combustion. In all those cases, a considerable amount of carbon dioxide emerges. Carbon dioxide gives rise to the greenhouse effect in the atmosphere and promotes variations in Earth's climate. The climate of the Earth is reliably observed by all ecologists in the world to change toward the global warming. This warming is accompanied by an instability of weather, namely, heavy rains or droughts, strong frosts or heats, and the increase of the global sea level [6] (see Figs. 1 and 2). In Fig. 3, the continental temperature changes are depicted.

Thus, the mankind faces a large problem: **How can the capacity of energy production be increased without any damage the ecology of our planet?** Modern science can propose a resolution of this problem by producing energy at nuclear power plants. It will be recalled that the latter do not require oxygen for their exploitation, and they do not produce greenhouse gases. Of course, the problem of catching the greenhouse CO_2 gas produced by fuel-burning power plants and other energy sources remains challenging.

Another important direction in the solution of the energy problem is the conversion of solar energy with the help of semiconductor elements. Within the last years, their efficiency increased from 10% to 30%. That is why, it is reasonable to use this method of energy generation where it is possible. As one can see from Table 1, more than 30% of the power expenditure is associated with the personal consumption and various services. In other words, this is the energy consumption for the heating or cooling of premises, cooking, and so on, when large point energy sources

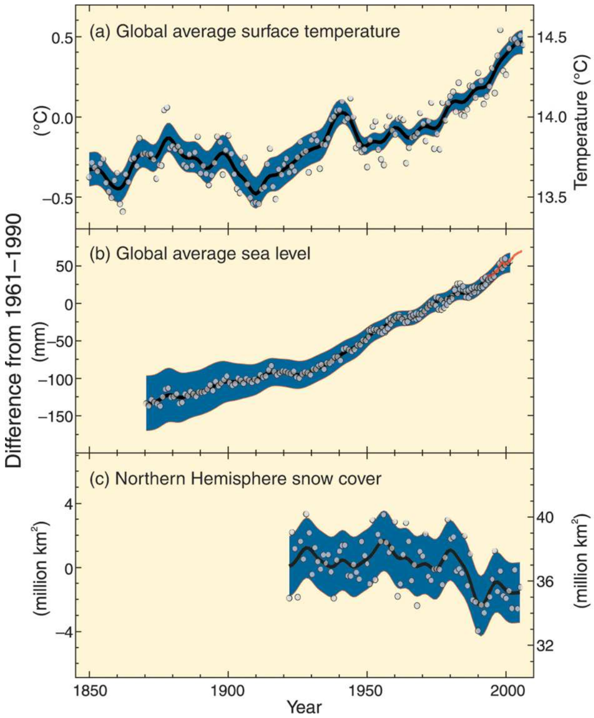

Fig. 1. Observed changes in the global average surface temperature (*a*); global average sea level from tide gauge (blue) and satellite (red) data (*b*) and the Northern Hemisphere snow cover for March-April (Taken from work [6]) (*c*)

Table 2. **Energy production per capita [5]**

Country	Population, mln	Energy production E, 10^{12} Wh	E per capita, kWh/person	Lifespan (year)	
				men	women
Japan	120	863	8600	79	86
USA	319	4100	13000	75	81
France	64	545	8500	78	84
Canada	34	577	17000	77	84
Ukraine	42	180	4200	62	74
Russia	146	920	6300	64	76

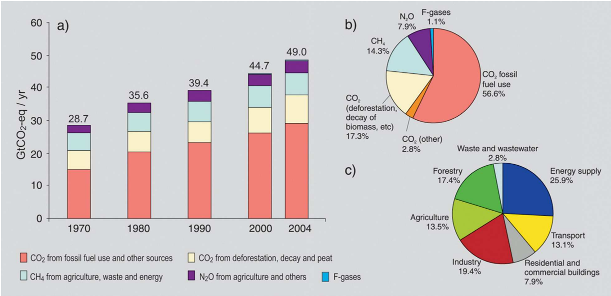

Fig. 2. Global annual emissions of anthropogenic greenhouse gases (GHGs) from 1970 to 2004 (*a*). Share of different anthropogenic GHGs in total emissions in 2004 in terms of carbon dioxide equivalents (CO_2-eq) (*b*). Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2-eq. (Forestry includes deforestation) (Taken from work [6]) (*c*)

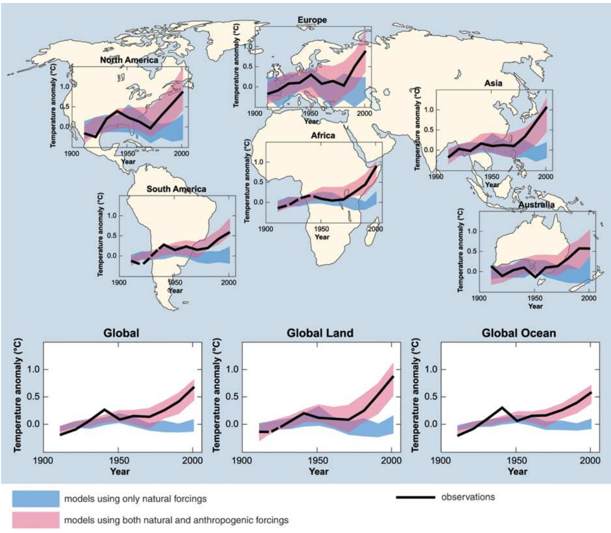

Fig. 3. Comparison of the observed continental- and global-scale changes in the surface temperature with the results simulated by climate models using either natural or both natural and anthropogenic forcings. (Taken from work [6])

are not required. In those cases, the application of solar energy is important. A shortcoming of solar power engineering is the circumstance that it is not active at night, and the energy generation depends on weather. In other words, the solar power engineering ought to be combined with permanent energy sources. We would like to emphasize that no oxygen is spent when the solar energy is converted into the electric one.

The basic difference of nuclear energy sources from the sources of other types is the generation of a huge amount of energy at one place. For this reason, nuclear power plants can solve problems that arise in chemical and metallurgy industries, as well as in similar branches, and supply the electric power to megacities throughout the world.

Note that, in the countries with hot climate, an important role can be played by the application of geothermal fuel and the production of hot water under minimum conditions. A technology for the heating of premises by geothermal energy has been developed and implemented in practice at the National Academy of Sciences of Ukraine.

The types of energy sources proposed by modern science and engineering are summarized in Table 3.

4. Atomic Energy for Military Purposes: USA versus USSR

4.1. Manhattan project

It is well known that the development of power systems that would use a new energy source (nuclear energy) started from the works aimed at creating an atomic bomb. In 1934, Otto Hahn and Fritz Strassmann began their research on the irradiation of uranium with neutrons. In so doing, they hoped to obtain transuranium elements. The results of experiment showed that elements with atomic masses approximately half as much as that of uranium were formed at that. In order to explain the results obtained, Hahn assumed that the uranium nucleus "bursted". On December 17, 1938, the scientists made the key experiment: the well-known fractionation of radium, barium, and mesothorium. The results obtained allowed Hahn to conclude that the uranium nucleus "bursted" and decayed into lighter elements. In such a way, the nuclear fission was discovered. The experimental results obtained by Hahn and Strassmann were published on January 6, 1939 and served as the indisputable proof of the uranium decay into lighter elements. The calculation of energies involved in this nuclear reaction confirmed the results obtained experimentally. Immediately after the discovery, Hahn informed Lise Meitner, who together with her nephew Otto Frisch published a theoretical substantiation of this phenomenon in the issue of the English journal "Nature" (February 11, 1939).

In the course of this fission reaction, a huge amount of energy, about 200 MeV per reaction event, is released. It became clear for nuclear scientists that

Table 3. **Types of energy sources**

Energy source	Resource (years)	Shortcomings
Coal, oil, gas	Hundreds of years, point sources	CO_2 production, climate change
Nuclear power engineering	Hundreds of years, point sources	Insufficient safety
Water power engineering	Lifeime of Earth's steady orbit	Flooding of lands. No resources in Europe
Solar power engineering	Lifeime of Earth's steady orbit	No powerful point sources, expensively, operation irregularity, taking of lands for non-agriculture purposes
Wind power engineering	Lifeime of Earth's steady orbit	No powerful point sources, operation irregularity, harmful for nature
Biofuel crops	Lifeime of Earth's steady orbit	Taking of lands

uranium belongs to energy carriers with a huge energy content per unit mass. Therefore, weapon with a tremendous destructive potential could be created on its basis.

Let us also recall that it was a period when A. Hitler initiated the World War II. Before the war, German physicists had a lot of outstanding achievements, including those in nuclear physics. As a result of Hitler's antisemitic policy, many scientists from Germany, Italy, and other European countries were forced to emigrate, mainly, to the USA. The emigrated physicists understood well that the creation of an atomic bomb in Germany was quite possible because of the developed industry in Germany and a large group of nuclear physicists and engineers. The emigrated physicists understood well that no moral principles could prohibit A. Hitler from a wide application of nuclear weapons. For this reason, Leó Szilárd, Eugene Wigner, and Edward Teller asked Albert Einstein to write a letter to the American president F.D. Roosevelt with a request to start works on the creation of a nuclear weapon in America as a counterbalance to its possible creation in Germany.

Albert Einstein, when signing this letter, had certain doubts concerning the future of the atomic weapon. He understood well that, after its creation, the application of the atomic weapon would be controlled by the government rather than scientists. However, the danger of the atomic weapon creation in Germany was an important reason to sign the letter. Einstein's letter initiated the Manhattan project, the aim of which was the creation of an atomic bomb. The outstanding American physicist Robert Oppenheimer was appointed the scientific director of the project. General Leslie Groves was made responsible for the management part of the work and the protection of data privacy.

Table 4. **The most acceptable technologies**

Source	Economy	Climate
Coal, oil, gas	Pro	Contra
Nuclear power engineering	Pro	Pro*
Solar power engineering†	Pro‡	Pro

* Physically safe NPPs are required.
† Assuming semiconductor converters (30%).
‡ For housekeeping, provided a consideratble reduction of the price per kWh.

The following physicists with the worldwide reputation took part in the American atomic project: Rudolf Peierls, Otto Frisch, Edward Teller, Enrico Fermi, Niels Bohr, Klaus Fuchs, Leó Szilárd, John von Neumann, Richard Feynman, Isidor Rabi, Stanisław Ulam, Victor Weisskopf, Edwin McMillan, Robert Oppenheimer, John Lawrence, George Kistiakowsky, Ernest Lawrence, Richard Roberts, Alexander Sachs, Hans Bethe, Sylvan Schweber, Vannevar Bush, John Cockcroft, and others. From this list, one can see that approximately half of major participants were immigrants from Europe.

While performing this project, the American physicists, engineers, and technicians were forced to pioneer in the solution of a variety of new fundamental, applied, and technical problems. Let us mention some of them.

1. The determination of critical masses for uranium-235 and plutonium-239.

2. The development of methods for producing uranium-235 and plutonium-239.

R. Oppenheimer *E. Fermi* *E. Teller* *L. Szilard* *L. Groves*

Fig. 4. Principal members of the American nuclear project

3. The designing of atomic bomb.

We recall that the critical mass is the amount of U-235 or Pu-239 in a spherical specimen, at which the number of neutrons generated in the specimen volume per unit time becomes equal to the number of neutrons escaping from the specimen within the same time interval. For the determination of the critical mass, the crucial role is played by the number of neutrons released in a fission event. For the first time, the calculation of the critical mass for uranium-235 was carried out by Otto Frisch and Rudolf Peierls in Great Britain in June, 1939. They obtained a value of 10 kg. At present, the critical masses of uranium-235 and plutonium-239 are considered to equal the following values: the critical mass for a spherical specimen of pure metallic plutonium-239 equals 11 kg (the diameter of the sphere equals 10 cm), and 50 kg for uranium-235 (the diameter of the sphere equals 17 cm).

The next problem to be solved was the obtaining of uranium-235 from natural uranium and the production of plutonium-239. Uranium-235 is contained in natural uranium with a content of 0.7%. For its separation, the American scientists applied the gas diffusion method (in November, 1942).

Plutonium-239 is produced from uranium-238 in the nuclear reactor. The first nuclear reactor was constructed by E. Fermi. The construction of the reactor was started in the metallurgical laboratory of the Chicago University in October, 1942 and was ended on December 2, 1942. Since plutonium, by its chemical properties, differs from uranium, it was removed from the reactor using chemical methods.

Hence, before 1943, the second problem associated with the creation of the atomic weapon was solved at a basic level.

By 1945, three bombs were fabricated in the USA. One of them was made on the basis of uranium-235, and two others on the basis of plutonium-239. In 1945, the test of a plutonium bomb was carried out, which demonstrated a tremendous destructive potential of the nuclear weapon.

The military application of the new type of weapons was performed on August 6 and 9, 1945, when two atomic bombs were dropped on the Japanese cities Hiroshima and Nagasaki. There were no military units in those cities at that time; only the civilians. The total number of killed civilians amounted to 120 thousand people in Hiroshima and from 60 to 70 thousand people in Nagasaki [7]. In our opinion, those bombardments of Japanese cities performed by the order of the US president Harry Truman are a crime.

The official version of the US government consisted in that the bombardments were aimed at forcing the war to the end and, hence, reducing the American army losses. But there is another version. The purpose of those atomic bombardments was to demonstrate military capabilities of the new type of weapons, which only the Americans possessed at that time, to the whole world and, first of all, to the Soviet Union. After the atomic bombardments, Japan capitulated.

Figure 4 demonstrates the principal members of the Manhattan project.

Julius Robert Oppenheimer (April 22, 1904–February 18, 1967). American physicist-theoretician. He is widely known as a scientific director of the Manhattan project aimed at developing the first samples of nuclear weapon during the World War II. For this reason, Oppenheimer is often called the "father of the atomic bomb".

Enrico Fermi (September 29, 1901–November 28, 1954). American and Italian physicist, who is most known owing to the creation of the first-ever nuclear reactor.

Edward Teller (January 15, 1908–September 9, 2003). American and Hungarian physicist. The general manager of works on the creation of the American hydrogen bomb.

Leó Szilárd (February 11, 1898–May 30, 1964). Together with Enrico Fermi, he determined the critical mass of U-235 and participated in the creation of the first nuclear reactor.

Leslie Richard Groves (August 17, 1896–July 13, 1970). Lieutenant General of the US army. In 1942–1947, he was the military director of the program on the creation of the nuclear weapon (the Manhattan project).

The creation of atomic weapons by American physicists was stimulated by a real danger of the creation of this weapon in the fascist Germany. One of the problems that naturally arose at the creation of the atomic weapon was the ethical problem of its application. This problem was actively discussed in the USA and the USSR. After the bombardments of Hiroshima and Nagasaki, Oppenheimer, Einstein, Joliot-Curie, and a number of other physicists and outstanding scientists deprecated the bomb application. A broad campaign against the application of atomic weapons was organized in the USSR in the post-war years.

4.2. Soviet atomic project [8]

The Soviet atomic project was formally started in 1942. Till 1945, the main activity in the framework of the Project was associated with the study of data gathered by the intelligence service (Kurchatov, Khariton). The formation of the Project staff was another important task. It will be recalled that the Soviet Union made a hard war against Germany at that time. Many experts in nuclear physics were at the front. At the request of I.V. Kurchatov, I.V. Stalin issued a decree that allowed the required experts to be withdrawn from the front for working in the Project. Active works on the creation of the atomic weapon in the USSR were started in December, 1945, when I.V. Stalin charged L.P. Beriya to supervise the Soviet atomic project.

It was already known by that time that the atomic bomb can be created. The main stages of its creation were also known: these are the construction of nuclear reactor for plutonium production and the creation of methods for obtaining uranium-235 from natural uranium raw materials. The problem to obtain fissionable materials was the major one for the bomb creation. Under the assistance of L.P. Beriya, Soviet physicists and engineers constructed industrial reactors for the plutonium production and industrial systems for the production of uranium-235 from natural uranium.

The volume of construction works can be characterized by the following fact. Many closed towns were built in the Chelyabinsk region. The construction works were carried out by prisoners. Let us recall again that all that was performed in the country, the economy of which had been destroyed by the war.

The first Soviet atomic bomb was an exact copy of the American plutonium bomb. It was tested in 1949.

The elimination of the US monopoly in this kind of weapons and, in such a way, the prevention of the World War III, in which this weapon would undoubtedly be applied, was a stimulus for Soviet scientists and engineers in the creation of atomic weapons. It is worth noting that, in 1945, General D.D. Eisenhower's staff, by the order of President Harry Truman, developed a plan of the nuclear war against the USSR. This plan was pioneered in a series of similar American plans. It assumed that 20–30 atomic bombs should be dropped on 20 Soviet cities: Moscow, Leningrad, Kyiv, Gor'kii, Sverdlovsk, Chelyabinsk, Novosibirsk, and others.

4.3. Hydrogen bomb. The history of Soviet hydrogen bomb

While writing this section, we substantially used the materials that were published in the first volume of the History of Soviet Atomic Project (HSAP), namely, in the papers "On the Creation of Soviet Hydrogen (Thermonuclear) Bomb" by Yu.B. Khariton, V.B. Adamskii, and Yu.N. Smirnov [9], "The Hydrogen Bomb: Who Gave Away the Secret?" by L.P. Feoktistov [10], and "Chronology of Significant Events in the History of Atomic Bomb Creation in USSR and USA" by G.A. Goncharov [11].

After the creation of the atomic bomb, active works on the creation of a hydrogen bomb were started in the Soviet Union. It should be recalled that the first thermonuclear device was exploded in the USA on November 1, 1952. This device was actually not a "bomb", but a laboratory specimen with a special design, the size of which was about a three-story building and which was filled with liquid deuterium.

On the contrary, the Soviet scientists created exactly a bomb. It was a finished device ready for the

Fig. 5. Photo of the first Soviet thermonuclear bomb RDS-1 tested on August 12, 1953 at 07:30 LT at the Semipalatinsk nuclear test site

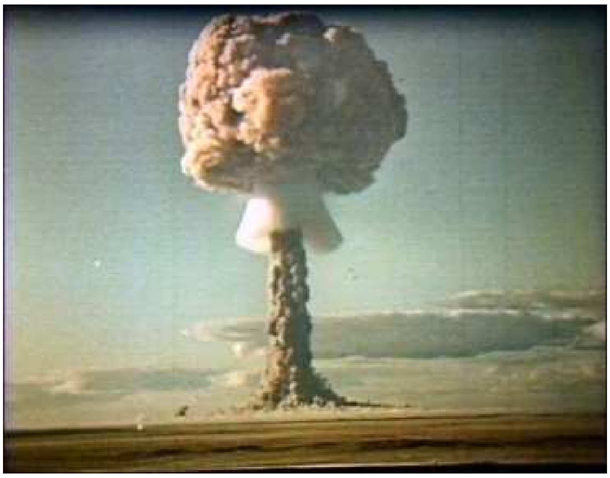

Fig. 6. RDS-1 test

practical application. The creation of the first Soviet hydrogen bomb was based on V.L. Ginzburg's constructive idea concerning the "preparation" of deuterium and tritium by exploding an ordinary atomic bomb. Namely, the hydrogen bomb was proposed to have a "layered" structure. A uranium or plutonium nuclear bomb was located at the center. A layer of lithium deuteride enveloped the center. The next layer was made from uranium-238. The explosion of atomic bomb invoked a high flux of neutrons. This neutron flux irradiated lithium deuteride and stimulated the production of tritium in it. The uranium-238 shell prevented this construction from "flying away". All works on the creation of a hydrogen bomb were managed by A.D. Sakharov. The parameters of a hydrogen bomb were calculated by L.D. Landau and his group [1]. This hydrogen bomb was named "Sloika" (Layer Cake). The first Soviet transportable thermonuclear bomb was exploded in 1953 (Figs. 5 and 6).

Development of works on the creation of a hydrogen bomb in the USSR. (Yu.B. Khariton, V.B. Adamskii, and Yu.N. Smirnov "On the Creation of Soviet Hydrogen (Thermonuclear) Bomb" [9].)

At the beginning of 1954, a meeting was held concerning the project of the Soviet hydrogen bomb, which was called "Truba" (Pipe). This project was proposed by I.I .Gurevich, Ya.B. Zeldovich, I.Ya. Pomeranchuk, and Yu.B. Khariton in 1946. A pipe is filled with deuterium and exploded from one of its ends by an atomic bomb. An attractive side of this project consisted in the absence of restrictions on the bomb yield.

The meeting was opened by I.V. Kurchatov. At this meeting, the project Truba "was buried" as having no promising variants. The project "Sloika" was also discussed. The latter was also found to have no promising prospects. Kurchatov suggested to search for new ideas.

In 1950, Teller, who also considered a project of a pipe-like bomb, came to the same conclusion. After his calculations carried out together with Fermi, Ulam, and Bethe, Teller understood that such a project has no prospects.

The Deputy Minister of the Sredmash A.P. Zavenyagin proposed to compress the thermonuclear fuel using nuclear explosions. A.D. Sakharov called the idea of thermonuclear fuel compression by means of a nuclear explosion as "the third idea". During the first half of 1955, the whole staff of the departments headed by Zeldovich and Sakharov was working in the "brain storm" regime at the problem of nuclear fuel compression. The very idea of nuclear fuel compression with the use of the light pressure had simultaneously come to a few physicists, including Sakharov. The latter justly marked in his memoirs that after the work has been jointly done, and done

[1] A bomb construction similar to Ginzburg's one was independently proposed by a Soviet Army soldier O.A. Lavrentiev. It was done also in 1949, but A. Sakharov obtained it after Ginzburg's message. See the movie "Secret physicists. O. Lavrentiev" (National Science Center "Kharkiv Institute of Physics and Technology").

well, the priority should not be searched. The result obtained by the Soviet theoreticians from Sakharov and Zeldovich's departments coincided with Teller–Ulam's idea to compress the thermonuclear fuel by the light pressure of a nuclear explosion.

By the summer 1955, theoretical calculations had been completed. Experimental works on the creation of a hydrogen bomb of a new type without restrictions on its yield were started. Such a bomb had been tested in the USSR earlier than in the USA.

The stages of the creation of a hydrogen bomb in the USSR [9]:

1. Sloika (1953).
2. Development of Sloika. A negative result (1954).
3. Closure of the "Truba" project (1954).
4. Early works on the thermonuclear charge compression by a nuclear explosion (1955).
5. An idea to use radiation rather than explosion products for compression (1955).
6. Brain storm and victory (November 22, 1955).

In the conclusion of this section, we quote a citation from Feoktistov's work [10]: "While estimating that period and the influence of the American 'factor' on our development, I may definitely say that we did not have any drawings or exact data that had been obtained from outside. At the same time, we were not the same as at Fuchs' and first atomic bomb's period, but considerably more intelligent and ready to perceive hints and semihints. I cannot help feeling that we were not quite independent at that time" [10].

Finally, we note that, in Goncharov's work [11], rather a detailed picture of works on a hydrogen bomb in the USSR and the USA is given. The results of Goncharov's researches were agreed with American physicists. They did not mention any American "factor". For this reason, work [9] was taken as a basis [2].

Tsar-bomb. The "Tsar-bomb" was created in the Soviet Union and tested in the Novaya Zemlya archipelago on October 30, 1961. The bomb yield amounted to 58 Mt. It was delivered to the test place by a Tu-95 bomber. At the explosion, 97% of the device energy was released as a result of the thermonuclear reaction; it was the maximum value for all tested devices. The "Tsar-bomb" was the most powerful explosive device ever created and tested on the Earth.

The creation of such a weapon has demonstrated the senselessness of further works on nuclear bombs in both the USSR and the USA, and the necessity to ban its application. In other words, the creation of "Tsar-bomb" became one of the arguments for the termination of the arms race. Unfortunately, the nuclear arms race and the development of systems to deliver nuclear weapons (intercontinental missiles) continued as long as to the end of the 20th century.

Figure 7 demonstrates the principal members of the Soviet thermonuclear bomb project.

Igor Vasil'evich Kurchatov (January 8, 1903–February 7, 1960). Soviet physicist, the "father" of the Soviet atomic bomb. He was the founder and the first director of the Institute of Atomic Energy (1943–1960), the principal scientific director of the atomic project in the USSR, one of the founders of peaceful uses of nuclear energy.

Yulii Borisovich Khariton (February 14, 1904–December 18, 1996). Since 1946, the chief designer and the scientific director of Design Department-11 (Arzamas-16) at the Laboratory No. 2 of the Academy of Sciences of the USSR in a town of Sarov. The best physicists of the USSR were engaged in the work on the realization of the nuclear-weapon program under his guidance. Together with Kurchatov, he is the "father of the Soviet atomic bomb.

Yakov Borisovich Zel'dovich (March 8, 1914–December 2, 1987). One of the creators of atomic and hydrogen bombs in the USSR.

Andrei Dmitrievich Sakharov (May 21, 1921–December 14, 1989). Soviet physicist, the head of works on the creation of the Soviet hydrogen bomb.

Lavrentii Pavlovich Beriya (March 17, 1899–December 23, 1953). In 1944, I.V. Stalin charged him to "supervise the development of works on uranium". He was the head of the Soviet atomic program and the Soviet intelligence service.

During the World War II, German scientists and engineers did not manage to create an atomic bomb. The reason was that neither Werner Heisen-

[2] After this review had been written, we came to know about G.E. Gorelik's work with V.I. Ritus's comments (see "Priroda", No. 7, 2007). In this work, some data are reported that it was Klaus Fuchs who put forward the idea of the fuel compression by light in 1948. He transferred this material on a hydrogen bomb to the USSR. Zeldovich was acquainted with this material, but probably did not understand it at that time. It is unknown whether Sakharov knew about those materials. Hans Bethe, the Nobel Laureate in physics and one of the principal members of the Manhattan project, called K. Fuchs the most prominent physicist of this project.

Fig. 7. Principal members of the Soviet nuclear project

berg, the head of the German project on the creation of atomic bomb, nor other German physicists could understand how it was possible to obtain uranium-235 or plutonium-239 in the sufficient amount. Later, the atomic weapon was also created in Great Britain, France, and China.

Military-oriented works resulted in the creation of a nuclear reactor as an essentially new device for producing energy by using nuclear forces in uranium.

5. Peaceful Use of Nuclear Energy

Nowadays, nuclear power engineering (NPE) became an important source of electric energy. At present, almost 440 nuclear blocks of various capacities are exploited at 194 nuclear power plants (NPPs) in 31 countries over the world. Their total electric power amounts to 370,000 MW. The fraction of NPPs in the total world electric energy production was maximum (17%) in 1993 and decreased to 10% in 2012 [3].

In comparison with the conventional energy sources, the nuclear power plants (NPPs) have the following advantages. First, they are powerful point energy sources, which is very important for large energy consumers, namely, metallurgical and chemical plants, undergrounds, and so forth. A second positive characteristic of NPPs is the fact that oxygen is not consumed in the course of electric energy generation. It should be recalled that oxygen is necessary for coal, oil, or gas thermal power stations to function (the combustion reaction). For 1 kg of coal, gas, or oil to be burnt, an amount of 2.7, 4, or 3.4 kg, respectively, of oxygen is required. Another advantage of nuclear power plants is a lower cost of produced energy per kWh in comparison with that produced at coal, oil, or gas thermal power stations. The cost of energy produced by wind power stations or solar power stations with semiconductor devices is also much higher. The corresponding data for Ukraine are as follows [14]. The cost of produced electric energy amounts to 22.2 kop/kWh for nuclear power stations, 68 kop/kWh for thermal power stations, 124 kop/kWh for wind stations, and 511 kop/kWh for solar power stations. The cost of energy produced at hydroelectric power stations is almost identical to that for nuclear power plants if the transferred territories are not taken into account and equals 20.6 kop/kWt. However, there are no territories in Ukraine for building new hydroelectric power stations.

Let us dwell on the specific features of the nuclear electric energy production in some countries. The largest number of nuclear power plants and nuclear blocks is in the USA: 103 nuclear power units at 66 nuclear power plants. They generate almost 20% of the total electric energy in the country [3].

In France, 58 power units are used at 19 nuclear power stations, which generate 74% of the total electric energy [3]. Since the power of modern nuclear power units is noncontrollable, the total amount of produce electric energy should be supplemented by thermal power stations with a controllable power, which is important for the working at peak loads. In France, the fraction of controllable power in the electric energy production equals 26%.

Canada exploited 19 CANDU reactors. Heavy water is used in them as a neutron moderator.

The government of China announced about the creation of a good many new nuclear reactors in the country in order to drastically increase the electric energy production by nuclear power plants. We recall that only 2% of electric energy is generated at NPPs in this country today. According to the IAEA data for 2013, 29 of 68 blocks constructed throughout the world are located in China. The Chinese government plans that, by 2040, 50% of the total electric energy produced in the world should be generated at the nuclear power plants in China.

5.1. Dangers of Nuclear Power Engineering

Within the period of their exploitation, plenty of accidents (several hundreds) took place at nuclear power plants and nuclear reactors at submarines, ships, and research institutes. Their analysis shows that most of them, approximately 70%, were associated with the human factor, about 20% with technical malfunctions, and about 10% with a random combination of circumstances. For the better understanding of this section, we recommend to look through Appendix 1.

Three the largest accidents at nuclear power plants are distinguished. These are the Three Mile Island accident in the USA (March 29, 1979), the Chernobyl accident in Ukraine (26 April, 1986), and the Fukushima accident in Japan (March 11, 2011). Their analysis, as well as the analysis of other, not so damaging incidents, shows that the accident and the catastrophe are separated by an exclusively short time interval, after which the process becomes irreversible.

As accidents, we will call events at power stations, after which the station exploitation can be resumed. Catastrophes are events, after which the station cannot be restored. Moreover, the expenses for the elimination of catastrophe consequences call into question the economic efficiency of the NPP usage. In particular, the catastrophe at the Three Mile Island resulted in that the construction of new nuclear plants in the USA was practically stopped. It was so because the expenses for the elimination of its consequences have exceeded the economic gain obtained from the work of this station within the whole period of its exploitation.

After the disaster at the Chernobyl nuclear power plant, the construction of nuclear stations was slowed down throughout the world. The expenses for the elimination of the consequences of this catastrophe amounted to about US$12 billion. These expenses considerably exceeded incomes obtained from all nuclear stations in Ukraine. But before 1992, the destiny of Ukraine was not so severe, because the corresponding expenses for the elimination of the consequences of Chernobyl disaster were the responsibility of the USSR. Only in approximately 10 years after the catastrophe, the construction rates of nuclear power stations in the world were restored. Their construction is stimulated by economic, ecological, and physical advantages obtained, when the NPPs are functioning in a regular regime.

As was already mentioned, the safe functioning of a nuclear power plant is associated, first of all, with the human factor and with the technical reliability of power blocks. After the Chernobyl catastrophe, the community of employees in nuclear power engineering recognized the necessity to engage and to stimulate a highly skilled working personnel at NPPs. This movement was called the "Culture of Nuclear Safety and Security". The concept of nuclear safety culture is very wide and also includes a lot of elements ranging from the training of employees in nuclear industry to their high moral qualities. In our opinion, the nuclear safety culture should be combined with a system of material remuneration and services. Such a system should be developed by a team of experts in nuclear physics, physicians, economists, and psychologists.

Unfortunately, till now, there are no programs in the world that would purposefully study the elimination of consequences of accidents at NPPs. In particular, the managerial staff of the Fukushima nuclear power plant did not know the origin of the catastrophes at the Three Mile Island and Chernobyl NPPs, and the experience of the elimination of their consequences. As a result, they did not understand the danger of the delay in the cooling of nuclear reactors at the Fukushima NPP associated with the decay of radionuclides contained in them.

The experience on the elimination of accidents at NPPs must be carefully studied. At every nuclear plant, there must be a curriculum on the elimination of accident consequences. Regularly, with a frequency of not less than once a calendar year, the personnel have to be trained. The public should be informed about the state of every nuclear block in the country.

When being in France, one of the authors (VGB) had an opportunity to get acquainted with the moral and economic stimuli for both the employees at a nuclear power plant and inhabitants living around it. In particular, the latter pay less for the electric power. The same is valid for the price of hot water. Before the building of an NPP is started, the requests of the local population living around the future power plant such as the construction of roads, schools, and so on were satisfied. We recall that NPPs are powerful heat generators. At present, this heat is not used quite reasonably throughout the world. As a rule, NPPs are built near large rivers or seas, into which the generated heat is dumped.

The accident at the Fukushima NPP in Japan, which was provoked by natural cataclysms, whose probability was inadequately appreciated in the project, confirmed that such a source of danger as an NPP is incompatible with complacency and self-confidence. The accident at the Chernobyl NPP, the largest technogenic catastrophe, was not a result of a single fatal fortuity or a single simple exploitation mistake. Accidents at nuclear enterprises and NPPs in the USA, Canada, England, France, Japan, and the USSR happened before it as well. They could and should have served a lesson to people and warn them against the simplified approach to this most complicated problem of the present time.

Conclusions:

The 21st century testifies that science opens new technological opportunities for progress and making the human life quality better. In particular, not only nuclear power engineering but also electronics and information technologies gave rise to qualitative changes in mankind's life. New technical capabilities result in the appearance of new dangers to the human existence. This can be observed especially brightly on the example of nuclear power plants. The modern society uses nuclear power engineering now and will undoubtedly use it in the future, because this is an efficient tool to raise the life quality. The technical dangers of nuclear power engineering impose more strict requirements to the professional knowledge of employees at NPPs and the skill of its quick correct application. By their scale, mistakes in the domain of nuclear power engineering are comparable with those made while exploring the outer space.

Principles of stimulating everybody, from operators to locksmiths, to work diligently at nuclear power plants have to be elaborated. Such principles have to be developed by a group of scientists including physicians, psychologists, economists, and specialists in the domain of nuclear science. Not only moral but also rather serious material stimuli that would satisfy spiritual and material requirements of not only the employees at NPPs but also the members of their families (at least, for two generations: parents–children) have to be provided.

Important is a conclusion that a large-scale accident can occur at any NPP. One of the major dangers is the fusion of a nuclear reactor owing to accumulated radionuclides. Therefore, every NPP has to be supplied by a plan of technical actions aimed at the elimination of the accident and the protection of people against its consequences. Those plans should be made known in advance to the whole personnel of the NPP and inhabitants within the 30-km zone around the plant.

6. Main Shortcomings and Advantages of Modern Nuclear Reactors

Fast-neutron reactors are intensively developed nowadays. The amount of radioactive wastes is considerably smaller for them. Another of their advantages is associated with the application of uranium-238 as a fuel. It is evident that the amount of a fuel for NPPs is several hundred times larger in this case. Besides uranium, thorium can also be used in fast-neutron reactors. Thorium reserves are several tens times larger than those of uranium. Such reactors are expected to be proposed on the market in 10–15 years if we reckon from 2015.

Note also that our country possesses large uranium reserves, occupying the 11th place in the world. We also have a wide experience of the NPP exploitation, as well as a unique experience of eliminating the consequences of Chernobyl disaster. Ukraine has all facilities for training a highly skilled personnel ranging from technicians to operators for the work at NPPs.

Nuclear power engineering of the fourth generation is aimed at eliminating or at least substantially weakening three main threats:

• proliferation of technologies aimed at producing the weapon-grade isotopes and manufacturing nuclear weapons on their basis;

• large-scale radioactive contamination of the environment at accidents;

• radioactive contamination of the environment as a result of the unreliable storage or dispersion of radioactive wastes after a terrorist bombing attack.

Examples, when those threats were realized, are known. In particular, Ukraine went through the awful Chernobyl catastrophe, the consequences of which have not been eliminated till now. At the same time, having transferred to Russia all nuclear missile warheads and other nuclear weapons, our state became the first and, at present, remains the only country in the world that voluntarily refused to possess a nuclear arsenal. The nuclear policy of this kind is not typical. Until nuclear weapons remain the most powerful tool of the geopolitics and a means of the deterrence at confrontation, many non-nuclear states will aspire to possess this weapon.

The basic difference of nuclear power engineering of the next generation is its multilevel character. The construction of complexes with reactors for various purposes is supposed. By their basic destination, reactors can be classed into the following groups:

• power reactors, whose main function is the electric power generation;

• reactors-mutators for the deep burning out of weapon-grade isotopes and long-lived radioactive isotopes;

• reactors for manufacturing a non-polluting (carbon-free) fuel, i.e. hydrogen, by hydrolyzing water and for producing a synthetic hydrocarbonic fuel from coal.

Reactors of the same type can be so designed and "equipped" with such a fuel cycle that they would be capable to combine various functions (e.g., the production of electric power and the burning out of undesirable isotopes). The experience testifies that the specification of such high-tech equipment as reactors allows technological solutions concerning their usage to be simplified.

7. Physically Safe Reactor

An idea of creating a reactor, for which the physics of functioning would be safe, came to everybody who developed new devices for nuclear power engineering. One of the early propositions was: to combine the accelerator and the nuclear reactor. In this systen, the reactor should be in a subcritical state. The accelerator irradiates the substance in the reactor, transforms protons into neutrons, and, in such a manner, strengthens the neutron field. In the working regime of an accelerator, the neutron multiplication factor $k > 1$, as in the standard reactor. The transition to the working regime with $k = 1$ is realized by means of absorbing rods. In other words, the accelerator together with the system of absorbing rods makes this system completely similar to the ordinary nuclear reactor. An advantage of the former in comparison with the latter is a possibility to stop the nuclear chain reaction immediately (more precisely, within a very short time interval). It is so because the accelerator shut-down time is very short. Unfortunately, it was found later that this device cannot solve the problem of the creation of a physically safe reactor completely. The reason is associated with the fact that, like an ordinary reactor, a large quantity of radionuclides is accumulated in such reactor during its operation time. Those radionuclides continue to decay after the nuclear chain reaction is stopped. The decay energy is so high that it can melt the reactor. Just this scenario happened in the Fukushima accident. The chain reaction was stopped, but the cooling system failed. As a result, the reactor was heated up to a temperature of about 2000 °C.

Those considerations show that a physically safe reactor should combine a small reaction volume and the properties of a fast-neutron reactor, in which a small amount of radioactive elements is produced. A reactor of this type was proposed by L.P. Feoktistov [16, 17]. The Feoktistov reactor operates as follows. Uranium-238 is loaded into a cylindrical pipe. With the help of uranium-235, a nuclear reaction of fissile material breeding (it is of the same kind as in the fast-neutron reactor) is "ignited". Owing to the burning of uranium-235, uranium-238 transforms into plutonium-239, which is a fuel for the next process. As a result, a wave propagates, in which uranium-238 is permanently burned, whereas plutonium-239 is produced and burned out. The process runs in a small volume. The amount of produced radioactive elements is insignificant.

The processes running in the Feoktistov reactor were researched in detail at the National Science Center "Kharkiv Institute of Physics and Technology" under the direction of Academician A.I. Akhiezer. The Feoktistov nuclear reactor was found to work stably. The underground location of this reactor makes it physically safe, because it prohibits the spread of even a "small" amount of radionuclides into the environment. Kharkiv physicists (Academician N.F. Shulga, Professor S.P. Fomin, and others) showed that, in the course of the Feoktistov reactor functioning, a huge radiation dose affects the pipe material. In particular, the number of atomic displacements induced by radiation reaches a value of 200 cm^{-3}. Modern materials applied in nuclear power engineering can sustain only 100 displacements in 1 cm^3. For this reason, the creation of Feoktistov's reactor becomes hampered by the absence of a progress in the development of new nuclear-resistant materials. Note that the same difficulty is true for fast-neutron reactors as well.

In 10 years after Feoktistov, Edward Teller came to a similar idea [18]. However, thorium-232 rather than uranium-238 should be used in Teller's project. The calculations of Kharkiv physicists revealed that the Teller reactor is not functional. But if a mixture of 50% thorium-232 and 50% uranium-238 will be used as a fuel, the reactor will work. Note that Teller understood well the importance of physically safe reactors of the Feoktistov–Teller type. By 1990, there were more than 100 underground missile silos in Ukraine. In the 1990s, when their destruction was initiated, Teller sent his disciples to the Kharkiv Institute of Physics and Technology. The latter should explain the importance of physically safe reactors and the necessity of their underground arrangement to Kharkiv physicists. In Teller's opinion, the underground silos would be a perfect variant for the arrangement of the reactors concerned.

In 2001, Professor Hiroshi Sekimoto (Tokyo Institute of Technology) [19] came independently to Feoktistov's idea and began to actively work in this domain. His works promoted physically safe traveling-wave reactors to be dealt in a lot of countries throughout the world, including the USA, where the TerraPower company was founded. In 2006, the company announced that a traveling-wave reactor would be built by 2020. One of the TerraPower's primary investors is Bill Gates. In his opinion, reactors of this kind can help us to solve the problem of CO_2 control and preserve Earth's climate.

7.1. Morals of modern atomic scientists

The ethical standards of atomic scientists throughout the world were formed during a hard time and under very severe conditions. It was the period of the World War II, which left a strong mark on the ethical principles of atomic scientists. That is why, the application of nuclear energy was considered as a weapon at the first place and for peaceful purposes only afterward.

Scientists in each country had a specific stimulus for the creation of nuclear weapons: in the USA, to withstand Germany; and, in the USSR, to eliminate the US monopoly on the possession of such terrible weapons. The scientists in the United Kingdom had the same stimulus as the US scientists, whereas in France, as well as in China, the stimulus was similar to that for the USSR.

Now, the governments of the countries possessing nuclear weapons understand that the unleashing of a nuclear war is a way to the total destruction of life on the Earth. In other words, the world recognizes that the possession of nuclear weapons by different countries results in that it should never be applied. Instead, there is an urgent problem concerning the energy production and the environmental preservation.

In this connection, a considerable number of nuclear electric plants were built. It will be recalled that the nuclear pile is a complicated technical device, which operates at the explosion-quenching edge. This regime is governed by the number of neutrons that arise in the reactor every second. This number has to be strictly fixed and controllable by a special system. In the case of personnel's mistakes or at stochastic technical malfunctions, an accident may arise, and the professionalism of a personnel and the correctness of their actions are subjected to the most severe tests.

As was already mentioned, after the nuclear accident at the Chernobyl NPP, the world came to the understanding that the human factor plays a very important role in the prevention of nuclear catastrophes. World's nuclear community, under the auspices of the IAEA, put forward an idea of nuclear safety culture. This is rather a general concept that accumulates demands to the moral of any employee engaged in the nuclear industry. Those demands range, in particular, from a permanent improving of the owned knowledge to a skill of detecting all possible deviations in the reactor work from the normal regime and, especially, the ability to response to the most improbable events that could break the safe regime of operation of a nuclear reactor. The role of the nuclear safety culture was perceived once more after the nuclear catastrophe at the Fukushima NPP. France, the USA, and Finland have a rich experience on stimulating the employees of the nuclear industry to ensure the safe work of nuclear power plants.

7.2. Formation of ethical standards

The issue of scientists' participation in military engineering projects in order to create more and more efficient weapons is not new. At the dawn of civilization, Plinius Secundus Major wrote that the "scientific minds" of antiquity "have given wings to iron and taught it to fly", thereby having made "the most criminal artifice that has been devised by the human mind".

Science and technology are known to be neutral. Their achievements can be used by individual persons or separate governments for both good and evil. Quite often, there arose a moral problem of choice for the scientists in the past: to participate or not in researches that are potentially dangerous to the mankind; sometimes, directly in the creation of weapons. As usual, this choice was governed by the confidence in the moral neutrality of science, or the requirement of citizen-patriot's ethos, or a combination of the both; sometimes, by the issues of a professional carrier (prestige and material welfare) complicated by specific circumstances and own considerations. The scale and the scientific appeal of the military-engineering problem could have a lot to do with it (see p. 365 in work [8]).

Nuclear "ethics" was formed in the USA, when the World War II had already started, and in the USSR, when the Great Patriotic war was in full swing. Thereby, the civil ethics got the features of the military one. A noble purpose to leave the fascist Germany behind was a moral justification for the developers of nuclear weapons. The danger of creating the first atomic bomb in Germany was quite real in view of its powerful scientific and technological potentials, the availability of raw material resources, and the fact that the discovery of uranium fission was made by German scientists (see p. 365 in work [8]). Later, A.D. Sakharov recollected: "I wasn't a soldier in that war, but I felt like one in this scientific and technological war"; and "Sometimes Kurchatov said that we were soldiers, and it was not only a mere phrase" (see p. 366 in work [8]).

Hence, during its first decade, the Soviet nuclear ethos was formed under the conditions of a "leadership race". It aimed at reaching the nuclear parity. Only this parity could provide the defense capability of the country and form its basis (see p. 368 in work [8]).

Ethical problems include the protection of nuclear power engineering from those communities that do not have the slightest idea of what it is; in particular, the Greens. Physicists should not take up a passive position in this issue and permanently justify themselves against the charges of Greens. Till now, we always heard only questions and complaints from the Greens and justifications from physicists. This is a wrong policy, because, roughly speaking, physicists are playing an away game in this case. The openness policy together with an absolutely open and fair initiative consideration of existing problems will be better (see p. 371 in work [8]). Sakharov said that 100 last bombs must not be destroyed (otherwise, a very unstable situation will emerge, and somebody may want to use it) (see p. 373 in work [8]).

Perhaps the fact that nuclear fission had been discovered on the eve of the World War II has led to the situation where the attention was first focused on the development of nuclear weapons, rather than on nuclear power engineering. Surely, this military aspect left its mark on the development of whole industry (see p. 374 in work [8]).

APPENDIX 1.
Nuclear accidents

See Table 5. The table testifies that the main origin of nuclear accidents is the human factor: there were 17 accidents because of this factor, including the factor of ignorance. Notations SAS, RAS, and AAS stand for the Soviet, Russian, and American atomic submarines, respectively.

APPENDIX 2.
Quotations of atomic weapon creators

1. After the bombardments of Japanese cities:

Oppenheimer: "Mr. President, I feel I have blood on my hands".

Truman: "Never mind, this can be easily washed off with water".

(http://militera.lib.ru/research/orlov_as1/02.html)

2. Yu.B. Khariton:

"We have to know ten times more than we do".

(http://vikent.ru/author/131/)

3. When a "beating" of the alien to Marxism quantum physics was being planned, similarly to what was done earlier with genetics, Khariton complained to Beriya that this circumstance complicated works dealing with the weapon. Beriya flared up: "We will not allow assholes to interfere with your work!" Several times, Khariton succeeded in that Beriya "pardoned" physicists who made an ideological slip. Beriya gloomily asked: "Do you need him?" Once Beriya said to the Chief designer: "Yulii Borisovich, if you only knew the number of denunciations of you!" After a while, he added: "But I do not trust them".

4. E. Teller:

"I consider that the peacekeeping demands international treaties, and I consider the international treaties to be much more efficient if they start from the words "to do" rather than "not to do".

(http://wsyachina.narod.ru/history/kurch_1.html)

Table 5. **Analysis of nuclear accidents occurring from 1945 to 2011 and their origins (according to IAEA data)**

No.	Accident site	Date	Cause of accident	
			Human factor	Technical malfunctions
1	Atlantic Ocean, AAS SSN-593	10 Apr 1963		Unknown
2	Atlantic Ocean, AAS SSN-589	22 May 1968	Captain's mistakes	
3	Bay of Biscay, SAS K-8	08 Apr 1970		Inflammation
4	Pacific Ocean, SAS K-108 and AAS	22 Jun 1970	Wrong maneuver, collision of 2 ASs	
5	Ussuriisk, Chazhma Bay	10 Aug 1985	Breach of security at fuel recharging	Spontaneous nuclear reaction, explosion
6	Norway Sea, SAS K-278	07 Apr 1989		Underwater fire
7	Barents Sea, RAS Kursk	12 Aug 2000		Unknown
8	Atomic ice-breaker Lenin	03 Feb 1965	Operators' mistake	
9	Semipalatinsk, Kazakhstan	29 Aug 1949	Wrong calculation of explosion yield	
10	Bikini Atoll, Pacific Ocean	01 Mar 1954	Same	
11	Carlsbad, USA	10 Dec 1961	"	
12	Semipalatinsk, Kazakhstan	15 Jan 1965	"	
13	Aikhal, Yakutiya	24 Aug 1978	"	
14	Oak Ridge National Laboratory, USA	01 Sep 1944	Breakdown in process	Spontaneous nuclear reaction
15	Oak Ridge plant Y-12, USA	16 Jun 1958	Same	
16	Vinca, Yugoslavia	15 Oct 1958		Spontaneous nuclear reaction
17	Three Mile Island NPP, USA	28 Mar 1979	Breakdown in NPP repair policy	Equipment error
18	Chernobyl NPP, Ukraine	26 Apr 1986	Personnel mistakes	
19	NPP Fukushima, Japan	11 Mar 2011	Mistakes at reactor cooling*	
20	Chelyabinsk-65, USSR	21 Apr 1953		Spontaneous nuclear reaction
21	Same	19 Jun 1948		Technological bugs
22	"	04 Jan 1949	Violation of technological regulations	
23	Techa River, Chelyabinsk region.	03 Mar 1949	Criminal negligence of administration	
24	Chelyabinsk-65, USSR	29 Sep 1957	Errors in the technology of radioactive waste storage	No temperature control in the cooling system of tanks with radioactive wastes

* The staff had no knowledge about the accidents at Three Mile Island and Chernobyl NPPs.

† Radioactive contamination of the Techa River by liquid waste discharge. No calculations of the influence of radioactive waste on the health of people living along the river were made.

E. Teller:

"Today, the world became smaller. Science and engineering have made substantial progress. This fact allows a large amount of damage to be done to any country if anyone would like to do it. I believe that the preservation of peace cannot be achieved under present-day conditions by prohibiting the definite actions. Such mechanisms can be got round, and, as a whole, they have an instable character. I will rather believe that the world will be maintained by means of developing the common projects, interesting for the whole world. Hence, it has to become more evident that the world and the cooperation are good for all".

5. A.D. Sakharov:

"100 last bombs must not be destroyed (otherwise, a very unstable situation will emerge, and somebody may want to use it)" (p. 373).

A.D. Sakharov:

"I wasn't a soldier in that war (the World War II), but I felt like one in this scientific and technological war".

6. Kurchatov:

A.D. Sakharov recollected: "Sometimes, Kurchatov said that we were soldiers, and it was not only a mere phrase" (see p. 366 in work [8]).

7. Leó Szilárd, one of the participants of atomic bomb creation project, expressed his reaction to the bombardments of Japanese cities in the following emotional way:

"Suppose Germany had developed two [atomic] bombs before we had any bombs. Suppose Germany had dropped one bomb, say, on Rochester and the other one on Buffalo, and then, having run out of bombs, it would have lost the war. Can anyone doubt that we would then have defined the dropping of atomic bombs on cities as a war crime, and that we would have sentenced the Germans who were guilty of this crime to death at Nürnberg and hanged them?"

(http://members.peak.org/~danneng/decision/usnews.html)

APPENDIX 3.
Confrontation between the USA and the USSR (later, Russia) on world's ocean

It will be recalled that world's ocean occupies about 70% of Earth's surface. The USA traditionally paid much attention to their naval forces, including submarines.

The first American atomic submarine (AS) "Nautilus" was launched in 1954. On January 17, 1955, at 11 a.m. EST, the vessel put to sea for the first time and signaled a historic message: "Underway on nuclear power".

On August 3, 1958, having passed in the submerged position under the ice, "Nautilus" reached the North Pole and became the first vessel in the history of the mankind that passed this point of the Earth under its own power. The corresponding record in ship's log-book and the stamp issued in honor of this event are shown in Fig. 8.

To characterize ASs in general, let us quote the corresponding parameters for "Nautilus", which was not the best AS. "Nautilus" was a ship of 5000 tons displacement. A two-shaft nuclear installation with a total power of 9860 kW provided a power of 13800 h.p. and a velocity exceeding 20 knots (37 km/h). The submerged cruising range amounted to 25000 miles at a ^{235}U consumption of 450 g/month. Therefore, the cruising endurance practically depended only on the performance of air regeneration facilities, supplies of products, and team's stamina.

The shortcomings of "Nautilus" were as follows. (i) Vibration created by the working turbines was so strong that the sonar became useless already at a velocity of 4 knots (7.4 km/h). The vessel became deaf in this case. Moreover, high noise unmasked "Nautilus". (ii) The mass of nuclear installation turned out very large. As a result, some pieces of weapons and equipment provided in the project were not mounted in the "Nautilus". The biological protection, which included lead, steel, and other materials (about 740 tons) was the principal cause of weighting.

The second US AS "Seawolf" was built in 1957. Actually, this AS was also an experimental submarine. In the same 1957, the first serial ASs "Skate" were created in the USA. Four ASs of this series were built. In total, 41 strategic ASs were built in the USA in 1959–1967. The project of a multipurpose (hunter-killer) AS "Skipjack" was taken as a basis for the first series of strategic submarines. The subsequent series continued to develop this project, without essential modifications in the design and the power-plant of a ship. Basic attention was given to a gradual decrease of noise characteristics and the improvement of a missile complex. "Polaris A-1", "Polaris A-2", "Polaris A-3", "Poseidon C3", and "Trident 1 (C4)" missiles were sequentially used to good effect. Every strategic US AS carried 16 long-range ballistic missiles (from 2200 km for "Polaris A-1" to 7400 km for "Trident 1 (C4)"). As a result, the US ASs of the first generation considerably excelled the Soviet ones and quite corresponded to the Soviet ASs of the second generation.

During the period of "cold war", the US ASs were deployed in the Atlantic Ocean. At present (2014), they are deployed in the Pacific (60%) and Atlantic (40%) Oceans. The US ASs are used in the interaction with other US Navy forces; especially with ships equipped with high-precision weapons.

In the USSR, only eight ASs of the first generation, with each of them carrying three ballistic missiles, were built in 1958–1962. The range of shooting by R-13 missiles amounted to 650 km, and after their replacement in seven submarines by R-21 missiles to 1420 km. In 1967–1974, 150 ASs of the second generation with a missile shooting range varying from 2500 to 9000 km were built. In recent years, Russia built the submarine "Severodvinsk" and the strategic missile carrier "Yurii Dolgorukii". The total number of Russian ASs is smaller than that of the US ones. It is worth to note that the total number of NATO ASs exceeds 200.

In this Appendix, information taken from the Internet sites https://ru.wikipedia.org/wiki/Атомная_подводная_лодка and https://ru.wikipedia.org/wiki/USS_Nautilus_(SSN-571) was used.

APPENDIX 4.
Confrontation between the USA and the USSR (Russia) in space

Germany was the first country that applied missiles for military purposes. The famous rocket constructor Wernher von Braun created V-2 rockets, which could cover a distance of thousands of kilometers. They were controllable, though not precise enough to hit a specific target. During the World War II, Germany used V-2 rockets to bombard London. In total, about two thousand rockets were launched against London. As a result of those attacks, more than two thousand of London inhabitants were killed. Those figures testify to the exclusive inefficiency of German rockets. Those missiles were known to be unstable: approximately half of them reached London, whereas the others exploded in the air.

After the creation of nuclear submarines, it became clear that, if carrying missiles with atomic bombs, they would be especially efficient. We recall that the first Soviet nuclear submarine was intended for the destruction of American ports by making use of torpedoes with atomic bombs. The aspiration to arm the fleet and army with efficient means of delivery of nuclear weapons resulted in a competition between the USSR and the USA. The first success was achieved in the USSR. This fact was promoted by both the work of missile designers and the software for missile flights.

Academician M.V. Keldysh, the outstanding mathematician and the President of the Academy of Sciences of the USSR, was a chief "theoretician" of space exploration and nuclear program in the USSR. The most known designers of missiles were Academicians S.P. Korolev, M.K. Yangel', V.N. Chelomei, V.F. Utkin, S.P. Konyukhov, and A.D. Nadiradze.

Fig. 8

The first satellite of the Earth was launched in the Soviet Union. This start meant that the USSR had intercontinental missiles. The first human spaceflight was also performed in the USSR. This flight meant that the USSR possessed missiles that were capable to deliver a nuclear bomb anywhere on the globe.

Owing to the works at the design office "Yuzhnoe" (headed by Academician Utkin), unique SS-18 missiles were constructed. In the English-language sources, they were called "Satana" (Satan). Those missiles have ten MIRVed warheads with their own target coordinates. The works of Yangel' in Dnipropetrovsk were continued, in particular, by Chelomei.

The USSR also developed mortar missiles and built hundreds of launch facilities for intercontinental missiles. The Soviet designers also developed the launch of missiles from movable closed railway platforms. The list of achievements in the USSR (Russia) can be continued further; for instance, the creation of the "Topol" missile complex.

Note that the USA also has a number of outstanding achievements in astronautics. First of all, this is true for the first human mission to the Moon. There were six of such missions, and the American astronaut Neil Armstrong was the first person to walk on the Moon. His first words after the Moon landing were "That's one small step for (a) man, one giant leap for mankind".

One of the reasons why no nuclear collision happened between the USA and the USSR consisted in a relative parity in nuclear weapons and its delivery vehicles.

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