Figure 20. B P Konstantinov.

13. Conclusion

The activities of LFTI are a clear example that the Great Patriotic War was not won on battlefields and in the rear only, but also in laboratories and design bureaus. Notice that the developments of Soviet scientists were qualitatively at least as good as those accomplished by the allies, and in many cases better. What LFTI did for victory and increasing the military might of the country in the post-war years was a part of the enormous contribution to the creation of principally new defense systems and types of weapons that the institutes of the Academy of Sciences and their scientists made. [16]

It is difficult to find the right words that would describe the unprecedented activities of the Leningrad Branch of FTI in the city under siege and its role in the heroic defense of the city, in which mere survival was already an exploit.

The mission of LFTI was to serve as a forgery of specialists capable of implementing large-scale projects, be it radar, the degaussing of warships, or the Atomic Project. Working in wartime conditions, and in some cases even at the frontline, trained a unique generation of scientists with an acute sense of social duty, capable of assuming responsibility in critical situations. It was no accident that participation in these projects became an important stage of personal maturation for a huge constellation of brilliant scientists — prominent organizers of Soviet science.

[16] This titanic work was carried out under the conditions of evacuation of the scientific and industrial complex of the country, which had no precedent in world history in terms of the shortness of time available and the scale of the undertaking.

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References

1. D'yakov B B (Comp.) *Fiziko-Tekhnicheskii Institut v Gody Velikoi Otechestvennoi Voiny* (Physical Technical Institute in the Great Patriotic War) (St. Petersburg: Nauka, 2006)
2. Reinov N M *Fiziki — Uchitelya i Druz'ya* (Physics — Teachers and Friends) (Leningrad: Lenizdat, 1975)
3. Vitman R F, Kunitsyna E V (Ed.-Comp.) *Trudnyi Put' k Pobede. Fiztekhovtsy o Dnyakh Voiny* (Hard March to Victory. FizTekh People Remembering the War Times) (St. Petersburg: Izd. Politekhn. Univ., 2012)
4. Levshin B V *Sovetskaya Nauka v Gody Velikoi Otechestvennoi Voiny* (Soviet Science in the Years of the Great Patriotic War) (Moscow: Nauka, 1983) p. 57
5. Ryabev L D (Gen. Ed.), Kudinova L I (Comp.) *Atomnyi Proekt SSSR: Dokumenty i Materialy* (Atomic Project in the USSR. Documents and Materials) Vol. 1 *1938 – 1945* Pt. 1 (Moscow: Fizmatlit, 1998), Document No. 103
6. Koptev Yu I *Viza Bezopasnosti* (Visa of Safety) (St. Petersburg: Izd. Politekhn. Univ., 2011)
7. Biryukov N *Tanki — Frontu! Zapiski Sovetskogo Generala* (Tanks for the Front! Notes of a Soviet General) (Smolensk: Rusich, 2005)
8. Ryabev L D (Gen. Ed.), Kudinova L I (Comp.) *Atomnyi Proekt SSSR: Dokumenty i Materialy* (Atomic Project in the USSR. Documents and Materials) Vol. 1 *1938 – 1945* Pt. 1 (Moscow: Fizmatlit, 1998), Document No. 1
9. Kaftanov S V "Po trevoge" ("On alarm") *Khim. Zhizn* (6) 16 (1985)
10. Ryabev L D (Gen. Ed.), Kudinova L I (Comp.) *Atomnyi Proekt SSSR: Dokumenty i Materialy* (Atomic Project in the USSR. Documents and Materials) Vol. 1 *1938 – 1945* Pt. 1 (Moscow: Fizmatlit, 1998), Document No. 128
11. Grinberg A P, Frenkel V Ya *Igor' Vasil'evich Kurchatov v Fiziko-Tekhnicheskom Institute (1925 – 1943)* (Igor Vasil'evich Kurchatov at the Physical Technical Institute (1925 – 1943)) (Leningrad: Nauka, 1984) p. 151

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Major stages of the Atomic Project

R I Ilkaev

1. Introduction

The implementation of the Soviet Atomic Project was an issue of the greatest State priority. Its solution was based on mobilizing the best personnel and cadres in the country, including specialists of the highest qualification, scientists in academic research institutes and industrial institutions, and organizers of the defense industry in the USSR, who identified candidatures and trained research and managerial leaders at every level of the Atomic Project.

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Soviet military intelligence, which succeeded in obtaining and transferring valuable information not only concerning principal ideas but also concrete scientific and technological data, played an outstanding role in laying the groundwork for the development of Soviet nuclear weapons in the framework of the Atomic Project.

The Atomic Project (1943–1955) laid the foundation of the security of our country in the second half of the 20th century by eliminating the atomic and thermonuclear monopoly of the USA.

The main stages of the Soviet Atomic Project were:

1943–1949 — the creation, under I V Kurchatov's guidance, of Laboratory No. 2, of the research, technological, and industrial infrastructure of the nuclear industry; the creation of the first atomic bomb, RDS-1, on the basis of gas-dynamic implosion and the results of its testing;

1948–1953 — implementation of A D Sakharov's idea and construction of the prototype thermonuclear fusion module RDS-6r: realization for the first time of the ignition and burning of thermonuclear material;

1954–1955 — development and implementation of the principle of radiation-driven implosion; building of the RDS-37 prototype of the modern thermonuclear weapon.

This article describes the main features of the scientific implementation of each of the three stages of the Atomic Project.

2. Prehistory of the Atomic Project

The Atomic Project was built on a foundation composed of fundamental scientific discoveries and results, including the discovery of the neutron and nuclear fission, isotopes that can sustain a chain reaction, transuranic elements, the principles of isotope separation, the construction of the nuclear reactor, the creation of radiochemistry, and the study of the physics of explosive processes.

The idea of making the atomic bomb from U-235 isotopes and the components of the theory of atomic explosion, including the concept of the critical mass and nuclear chain reaction, were formulated by a number of European scientists, including Soviet ones, already at the end of the 1930s and the beginning of the 1940s. These ideas were initially discussed in open debates around the achievements of nuclear physics. Quite a few of researchers realized that uranium fission opened up new unexpected possibilities for creating nuclear weapons and power sources.

Soviet scientists actively worked in many areas of science that in the future proved to be key elements of the Atomic Project. The achievements of Soviet scientists in the nuclear sphere were at a world-class level, namely:

— the theory of the atomic nucleus was moving forward;

— nuclear isomers and the process of spontaneous fission of uranium were discovered;

— the theory of nuclear chain reactions was being developed;

— first-class research in the physics of explosives was conducted.

Among the pre-WWII research programs that had a significant impact on the implementation of the Atomic Project in the USSR, I wish to emphasize the work on the mechanisms of the processes of explosive transformations, the stability of dynamical states of combustion and detonation of explosives, and methods of excitation and transfer of detonation. An important contribution to this work was made by the founder of VNIIEF (now the Russian Federal Nuclear Center — All-Russian Research Institute of Experimental Physics) who headed the work of developing the atomic and thermonuclear weapons within the Atomic Project, Academician Yulii Borisovich Khariton.

In 1939–1940, Yu B Khariton, together with another hero among our outstanding scientists, who contributed enormously to the maturation and expansion of the program of nuclear-weapons project, Yakov Borisovich Zeldovich, carried out a number of pioneering studies on the development of the chain reaction in uranium-containing materials. Even at that early stage, Yu B Khariton and Ya B Zeldovich established that the exponential increase in the rate of the chain reaction is on the order of $10^7\ \mathrm{s}^{-1}$, and pointed to the need of solving the problem of rapid transition from the subcritical region of states of the fissile material to the supercritical region.

Among the most important events in the history of the Soviet Atomic Project were the proposals advanced by G N Flerov in his letter to I V Kurchatov in March–June 1942. These proposals formulated the conclusion on the feasibility of the fission chain reaction utilizing fast neutrons and U-235. The likely number of secondary neutrons in the nuclear fission of these isotopes caused by fast neutrons was estimated to be $\sim 2-3$; the probable effective fission cross section of these isotopes for fast neutrons was estimated as $\sigma_{\mathrm{f}} \sim 3$ b.

Flerov's proposals pointed out that an important obstacle to the implementation of a powerful explosive process of nuclear fission is the natural neutron background consisting of three components:

- cosmic-ray neutrons;
- spontaneous fission neutrons;
- neutrons accumulated in the process of α decay of nuclei in the reaction α, n.

G N Flerov noted the importance of the effect of the level of supercriticality at the moment of explosion and of the time of expansion of the active material during the explosion on the energy release in the nuclear explosion.

3. Laboratory No. 2 of the USSR Academy of Sciences

In 1942–1943, crucial decisions were made at the highest levels of the State, which determined the deployment of work on the Soviet Atomic Project. The first such decision was taken on 28 September 1942, as the Order No. 2352ts of the State Defense Committee (GKO): "On organizing the works on uranium".

The GKO order of 11 February 1943 said: "In order to promote more successful work on uranium, Cdes Pervukhin M G and Kaftanov S V are made responsible for the everyday management of uranium work and systematic assistance to the special atomic nucleus laboratory of the USSR Academy of Sciences (AS) ... Professor Kurchatov I V is charged with the responsibility for the scientific supervision of uranium works ..." [1].

A significant step in strengthening the organizational structure of the work on the Atomic Project was the appointment of Igor' Vasil'evich Kurchatov as Chief of the Special Atomic Nucleus Laboratory (Laboratory No. 2 under the AS USSR). This appointment was finalized on 10 March 1943 by Order No. 122 for AS USSR.

A I Alikhanov appears to have been the first in the USSR to consider in early 1944 the possibility of building a means for countering nuclear weapons. In a memorandum dated 4 January 1944 and submitted to I V Kurchatov, A I Alikhanov proposed as one such method the irradiation of an atomic charge operating on the implosion principle by high-intensity neutron flux, which would cause premature neutron initiation of the explosive charge and reduce its energy release by several orders of magnitude.

This memorandum noted that special measures of protection against such exposure can be taken in the atomic bomb, such as surrounding the bomb with a layer of hydrogen-rich substance or burying it several meters in the ground.

In March 1945, I V Kurchatov, after a review and analysis of new intelligence information on the atomic weapons program in the USA, noted that an atomic bomb can be set off by two different methods:

- by rapid convergence of two halves of the charge of uranium-235 or plutonium-239, initially placed at a distance of 0.5–1.0 m from each other;
- by densifying charges of uranium-235 or plutonium-239 by a powerful explosion of TNT surrounding these charges (gas-dynamic implosion).

The critical mass of fissile material could not be determined with the necessary accuracy; according to different estimates, it varies from 1 to 10 kg. Preliminary calculations indicated that the total weight of an atomic bomb containing from 5 to 10 kg of uranium-235 or plutonium, equivalent in its effect to the explosion of 10,000 to 50,000 tons of TNT, could be from 3 to 5 t.

On 7 April 1945, I V Kurchatov wrote that "we have just learnt about the implosion method and have started working on it; however, the advantages it has over the gun type method are already obvious." Most of the obtained material dealt with implosion. Specifically, Kurchatov received:

- a diagram of the propagation of detonation in the explosive and the process of deformation of the material surrounding the nuclear charge;
- a description of the compression of the body by the explosion and of the explosion itself;
- a description of the conditions (this was particularly significant) under which the explosion could be kept symmetric, as demanded by the idea of the method;
- a description of the phenomena of nonuniform action of the explosive wave and of techniques capable of removing this nonuniformity;
- a description of the technology of the experiments with explosives and the optics of explosive phenomena.

4. Developing the first RDS-1 atomic bomb

On 9 April 1946, The USSR Council of Ministers adopted classified Resolution No. 806-327 on setting up Design Bureau No. 11 (KB-11) of USSR AS Laboratory No. 2. This was the title of the organization which was destined to make the atomic bomb.

The same resolution appointed the command structure for KB-11: P M Zernov as its Chief, and Yu B Khariton as its Chief Designer.

Developing the atomic bomb imposed on the team the need to resolve an exceptionally wide range of physical and technical issues that involved a huge program of computational and theoretical studies, as well as design and experimental work.

First and foremost, it was necessary to study physical and chemical properties of fissile materials, to develop and approbate the casting and machining techniques.

There was a need to devise radiochemical techniques for extracting various fission products, to organize the production of polonium, and to elaborate the technology of building neutron sources.

The developers needed methods for determining the critical mass, a theory of explosion efficiency, and a theory of nuclear explosion in its entirety.

A very special field of the research work involved the theory of a converging detonation wave; various aspects of detonation of explosives; processes proceeding with the detonation wavefront traveling through an interface between two explosives; processing occurring in collisions of detonation waves emanating from different points, and the compressibility of metals at high pressures.

Experimental studies of the properties of substances incorporated in the physical implementation of the charge created the foundation for the verification of a physical notion about the processes occurring in the charge at the gas-dynamic stage.

Also needed were laboratory methods for the study of gas-dynamic processes that occur in exploding spherical charge of the explosive and methods for determining the parameters of a nuclear explosion conducted on the testing site.

A factor of critical importance for developing and producing the RDS -1 was the physical theory of the nuclear explosion; it was based on the equations of gas dynamics, diffusion of thermal radiation, and neutron transport. Meeting these challenges required the application of methods of approximate calculations. Most of the computations were conducted at the time in four specialized mathematical units:

- the Department of Approximate Calculations of the V A Steklov Institute of Mathematics of the AS USSR (headed by K A Semendyaev);
- the Computations Bureau of the Institute for Physical Problems headed by L D Landau and N N Meiman;
- the Mathematics Division of the Institute of Geophysics of the AS USSR headed by A N Tikhonov;
- the Department of Approximate Calculations of the Leningrad Branch of the V A Steklov Institute of Mathematics under the guidance of L V Kantorovich.

Building the infrastructure for the production of weapons-grade plutonium represented the major technological step in the realization of the Soviet nuclear weapons program. I V Kurchatov, analyzing the intelligence data, wrote in his memo to Vice Chairman of the Council of People's Commissars M G Pervukhin as early as 22 March 1943: "...they also point out that products of the combustion of nuclear fuel in the 'uranium pile' could be utilized as a material for a bomb instead of uranium-235... . The promise of this approach is extremely exciting..." [2].

As Laboratory No. 2 brought into operation in late 1944 its first cyclotron (a substantial contribution to its creation was made by L M Nemenov and V P Dzhelepov), it became possible to generate the first microscopic amounts of plutonium.

Launching the first F-1 atomic reactor on 25 December 1946 greatly expanded these capabilities. Up till then, it had already been established that plutonium accumulated in uranium in the course of its neutron irradiation can indeed be recovered by a realistic chemical method.

On 23 August 1946, the Government issued a resolution on building the first stages of plutonium-producing Plant No. 817 (Chelyabinsk-40; now Mayak enterprise).

On 19 June 1948, I V Kurchatov gave the command to launch the reactor A from 'level 0', and the power level of the reactor reached the designed value of 100 MW on June 22. The reactor took 1.8 years to build, exactly the same as its design and development.

The processes of radiochemical isolation of plutonium were developed under the direction of V G Khlopin in the Radium Institute of the Academy of Sciences in Leningrad.

The production technology for pure metallic plutonium was developed under the scientific guidance of A A Bochvar.

At 7:00 am on 29 August 1949, the RDS-1 charge exploded; this marked the successful completion of the development and testing of the first atomic bomb in the USSR.

The equipment used in the experiment made it possible to conduct optical observations and measurements of the heat flux, the parameters of the shockwave, and the characteristics of neutron radiation and gamma radiation; to determine the level of radioactive contamination of the area in the explosion site and along the trail of the mushroom cloud, and to study the impact factors of nuclear explosion on biological objects.

The energy release of the first Soviet atomic bomb was 22 kt of TNT.

The USSR thus came into possession of the technology of creating nuclear weapons and proved capable of setting up the industrial process of weapons production.

It is necessary to emphasize the principal importance of the fact that, even though the structure of the bomb charge was similar to that of the American bomb, its design, the mastering, the substantiation of the decisive physical processes, the production chain and technology were totally Soviet.

The history of the development of the first atomic bomb in the USSR was an example of a high degree of organization of all services of varying types, of the selfless approach of all participants in its creation, of their well-oiled interaction, and of the highest degree of responsibility for the job assigned to them.

Yu B Khariton wrote: "I am amazed and feel nothing less than awe looking now at what our people were able to accomplish in 1946–1949. It was very hard at the later stages, too. Nevertheless, the tension and heroism, the flight of creative potential, and the selfless dedication that manifested themselves during this period defy description in words..." [3].

5. Effect of the Atomic Project on scientific and technological programs in the USSR

The Atomic Project was tightly linked to large-scale research programs whose implementation resulted in intense progress in nuclear physics in the USSR.

On 4 March 1946, the USSR Council of People's Commissars (SNK) adopted a resolution, "On measures promoting expansion of cosmic-ray studies". Among other things, this program assumed the need to:

• clarify the nature of cosmic rays, their composition, and the processes through which ultrahigh-energy particles affect atomic nuclei;

• clarify the mechanism of nuclear transformations caused by cosmic rays;

• conduct work on solving the problem of the artificial generation of particle fluxes with energy comparable with the energy of cosmic rays.

The implementation of these tasks was assigned to S I Vavilov, A I Alikhanov, and D V Skobeltsyn. Among other things, they were instructed to set up the high-altitude Pamirs and Elbrus stations and an underground Moscow (subway) permanent station for exploring cosmic rays.

In August 1946, Stalin received a letter submitted for approval of the USSR Council of Ministers (CM) draft decision,"On designing and constructing a high-power resonance electron accelerator", designed by V I Veksler. The objective of building an accelerator with an electron energy of up to 1 GeV was to investigate the interaction of such electrons with atomic nuclei and the generation of mesons. The project was linked to the problem of creating nuclear weapons. The corresponding resolution of the USSR Council of Ministers was approved on 13 August 1946.

At the same time, another letter was submitted to Stalin requesting the approval of the USSR CM draft decision "On the construction of a high-power cyclotron" to a particle energy of up to 0.25 GeV, close to the energy of cosmic rays. It was assumed, among other things, that the facility would make it possible to "advance to the discovery of new physical phenomena (the discovery of new elements and new ways to extract atomic energy from sources cheaper than uranium)." This proposal was initiated by S I Vavilov, I V Kurchatov, A I Alikhanov, D V Skobeltsyn, and L A Artsimovich. The appropriate resolution was approved on 13 August 1946.

On 22 Aprill 1946, S I Vavilov, President of the USSR Academy of Sciences, submitted to the country's leadership a memorandum suggesting the organization of research in connection with the problem of the use of atomic energy. In fact, this memo discussed the mutual effects of the atomic weapons issue and the development of the fundamental scientific research. In particular, the memorandum [4]:

• requested mobilizing and reorganizing the mathematical side of the research program, first and foremost through using 'computerized' mathematics. In this connection, the memo argued in favor of the need to create within the AS USSR a special institute of 'computerized' mathematics and approximate calculations;

• pointed out that the chance to use atomic energy gives a way to concentrate enormous power in various experimental facilities, permitting the study of the properties of materials at extremely high pressures, densities, and temperatures, and the investigation of the propagation of radiation at enormous intensities;

• pointed to the need of investigating new methods of physical measurements of various physical quantities and phenomena;

• pointed out that such studies as the research on photochemical processes under irradiation by intense light, chemical processes under irradiation by neutrons and other particles, and chemical reactions and kinetics at very high pressures and temperatures will become very important;

• pointed to the need for intense use of seismology and seismic instruments for studying high-power explosions that accompany the quick release of nuclear energy;

• mentioned that huge stores of nuclear energy can be channelled into artificial climate change (melting of ice sheets, expansion of water reservoirs, creation of dams and centers of water condensation);

• emphasized the need for extensive research on the effects of radiation on humans, animals, and plants, and the development for these purposes of physiology, genetics, medicine, and agronomy.

In response to these proposals, a resolution of the USSR Council of Ministers on 16 October 1946 ordered the intensification of research on atomic nucleus and the use of nuclear energy in engineering, chemistry, medicine, and biology. Among the subjects to be intensely studied, the memorandum mentioned [5, pp. 76, 77]:

• search type work on direct conversion of radiation energy to other forms of energy;

• development of methods for the measurement of acoustic waves that accompany explosions at great distances;

• compressibility of metals at high and ultrahigh pressures;

• radiochemical studies;

• identification of uranium-carrying compounds in natural ores;

• study of radioactive decay in Earth's crust;

• photochemical processes in proteins caused by absorption of ultraviolet and corpuscular radiation and X-rays;

• effect of irradiation by ionizing radiation on growth and metabolism in plants and living organisms;

• effects of radioactive radiation on organs of the human body;

• effects of ionizing radiation on basic biological processes;

• therapeutic application of new types of radiation and radioactive substances.

Another group of studies that also belonged to this type of work were:

• development of methods, organization, and conduction of computer-assisted work;

• study of nuclear photoeffect in beryllium;

• study of the properties of neutrinos and their effects on nuclear processes;

• construction of standard equipment for radioactivity research;

• study of the optics of high-intensity light fluxes;

• study of metabolism in plants using tracer atoms.

In 1948, even before the creation of the first atomic bomb, a problem of studying the feasibility of developing effective countermeasures against atomic weapons was formulated. A proposal of this kind was advanced by Director of the Institute of Chemical Physics of the AS USSR, N N Semenov. The gist of this proposal was to concentrate maximum efforts on studying the action of fluxes of high-energy particles (neutrons, protons, deuterons) on fissile materials, and the processes of transmission of these fluxes through the outer layers of the atomic bomb and the atmosphere. In addition, N N Semenov noticed the need of creating special accelerators which would allow the generation of particles with energies above 100 MeV. The plan was to conduct the first stage of the experimental work on the facilities available at the time, and also to use the natural cosmic rays background. In August 1948, the USSR Council of Ministers adopted a resolution which ordered the Institute of Chemical Physics, the Physical Institute of the USSR Academy of Sciences, Laboratory No. 2, and the Physical Technical Institute of the Ukrainian Academy of Sciences to conduct in 1948–1949 the necessary research and development work on this issue. This project was the prototype of further efforts to develop the means of countering offensive nuclear weapons.

The problem of creating power reactors occupied a special place in the plans for the probable use of nuclear energy for peaceful purposes. In the USA, plans were drawn to begin constructing a gas-cooled nuclear power plant in Oak Ridge in April 1946, and to put it into operation in 1948.

In 1946, I V Kurchatov considered the possibility of using in the USSR a graphite-moderated reactor (which was then being developed with a view to accumulate weapons-grade plutonium) for power generation. In 1947, the first articles appeared in the press that the American side had begun work on designing an atomic power station, which provided a stimulus for deploying similar works in the USSR.

In 1949, Laboratory No. 2 evaluated possible approaches to creating power reactors for use in transport and for atomic power production. On 16 May 1949, a governmental resolution set the time to start work on the first atomic power station (AES). The AES was to be built at Obninsk, and the key role in its creation was played by Laboratory V (now known as State Scientific Center 'Institute for Physics and Power Engineering') and Laboratory No. 2 (now known as the Russian National Center 'Kurchatov Institute'). I V Kurchatov was appointed the scientific leader of the work on the first AES, and N A Dollezhal was appointed the Chief Designer of the reactor.

The following decision was taken in November 1949 at a meeting of the Special Committee of the USSR CM:

"In order to clarify the feasibility of using atomic energy for peaceful purposes (the feasibility of developing projects of power plants and engines using atomic energy), Cdes Kurchatov, Aleksandrov, Dollezhal, Bochvar, Zavenyagin, Pervukhin, and Emel'yanov are entrusted with the analysis of the issue relating to the possible redirection of research programs in this field and reporting their conclusions within a month to a meeting of the Special Committee" [5, p. 351].

Work soon started analyzing the options for building atomic power plants for navy ships and for nonmilitary vessels. These studies were stimulated by information from the USA on the large-scale work of designing an atomic-power submarine. This question required absolutely novel solutions — creating an efficient compact nuclear reactor satisfying severe restrictions imposed by the conditions of location and maintenance on board submarine.

6. Thermonuclear reinforcement. Sakharov's 'sloika'

On 12 August 1953, the country's first thermonuclear explosion went off at the Semipalatinsk test site. It was a test of Sakharov's famous 'sloika' — a thermonuclear (fusion) charge with a lackluster index RDS-6s. The test proved extremely successful: the 'gadget' power reached the 'upper limit' and lived up to every expectation of the ideologues, project leaders, scientists, engineers, and leaders of the country and of the atomic energy industry.

The central figure of the RDS-6s project was Andrei Dmitrievich Sakharov; for the successful implementation of this project, he received the highest state awards and became Full Member of the AS USSR by direct vote, skipping the step of Corresponding Member.

It is no exaggeration to say that the development of the RDS-6s was one of the most significant events of the 20th century, and a major step towards the creation of the nuclear shield for our country.

The RDS-6s was built using the principle of ionization compression of thermonuclear fuel ('idea 1' in Sakharov's terminology). Sakharov noted: "It was assumed that the detonation wave, originally created by the initiator (atomic explosion), compresses heavy water and uranium (by a factor of up to 7) and heats them to a temperature of about 10 keV (under conditions of matter–radiation equilibrium). Under isothermal conditions, pressures in uranium and heavy water equalize, which results in further significant compression of heavy water (about 7-fold) and in the corresponding acceleration of fusion reactions " [6, p. 30] (see also review [7]). This process was later called 'Sakharization'.

Later on, Sakharov proposed the much more efficient scheme of the sloika, based on implosion: the central domain is occupied by the detonator on which the heterogeneous layers of thermonuclear fuel and uranium are placed. The whole system is imploded by an explosive located outside the sloika. The sloika is initiated at the expense of the energy of explosion of the atomic detonator.

It was an exceptionally fruitful and pragmatic linkage of the fundamental physical ideas of Sakharization and implosion.

The dynamics of a multilayer charge were calculated by solving a set of hydrodynamic equations which included the continuity equation for the medium, Euler's equation of motion, and the energy conservation equation. The equation of energy conservation contained the energy source produced by neutron interactions with nuclei. The internal energy of the medium included the material energy and the radiation energy, while the radiation energy transfer in the medium was calculated in the approximation of radiative heat conductivity.

In 1950, E S Fradkin revised the equation of state of uranium in the framework of the Thomas–Fermi model. The Fradkin model showed that at temperatures characteristic of the stages of the ignition and burning of thermonuclear fuel, the material energy of the medium is about twice that of the original model. At the same temperature and density, the uranium pressure was practically the same in both models. This was an important example of how an improvement in the physical model can significantly change the description of the physical parameters of the basic processes.

One of the significant factors determining the success or failure in the development of the RDS-6s was the effect of mixing the thermonuclear layers and uranium layers during the nuclear explosion. Sakharov wrote: "Large accelerations develop in the course of expansion of a multilayer charge. As a result, interfaces between the layers become unstable... . The instability of the interface leads to mixing... . Mixing is a very unfavorable factor, since it reduces the rate of the thermonuclear reaction" [6, p. 69].

The mixing process could be divided into two stages:

• the starting stage of an exponential growth of initial perturbations;

• the stage of fully developed turbulent mixing.

These two stages were investigated by S Z Belen'kii: the first in 1949, and the second in 1949–1950.

Sakharov then remarked that "oblique incidence of the shock wave on a lighter layer creates an additional source of their mixing — tangential discontinuities. Unlike gravitational mixing, the influence of this factor is independent of small initial perturbations" [6, p. 70]. The significance of this factor was also evaluated by S Z Belen'kii (1949). It was shown that the role of this effect is comparable with that of 'gravitational' mixing.

The work on proving the viability of the design of the RDS-6s was the cornerstone of a new branch of knowledge in our country — computational mathematics and engineering (computer sciences). One of the leading developers of the RDS-6s, theoretical physicist Yu A Romanov, wrote: "...a new branch of science — computational mathematics — was born in the process of developing the RDS-6s. Even though the computer aids were primitive, numerical calculation of a very complex process — the explosion of a thermonuclear charge — became manageable owing to the creative contribution of the outstanding scientists M V Keldysh, A N Tikhonov, K A Semendyaev, and L V Kantorovich" [6, p. 169].

The State Commission chaired by I V Kurchatov decided to test the first RDS-6s hydrogen bomb on 12 August 1953 at 7:30 am local time at the Semipalatinsk test site.

A preliminary report on the results of the tests, prepared three days after the tests, was signed by I Kurchatov, Yu Khariton, K Shchelkin, I Tamm, A Sakharov, M Lavrent'ev, Ya Zeldovich, V Davidenko, V Komel'kov, N Dukhovoi, E Zababakhin, M Sadovskii, and N Bogoliubov. The report summarized the data of physical measurements and the overall pattern of the explosion. The conclusion drawn from the results of the analysis was that "the TNT equivalent of the RDS-6s gadget was between 350 and 400 thousand tons" [6, p. 112].

In 1953, an eminent physicist, H Bethe, chose these sincere words to characterize the creation of the RDS-6s: "I do not know how they managed to accomplish it. It is simply astounding that they were able to do it at all" [6, p. 117].

Notice that less than two months before the test of the RDS-6s, on 16 June 1953, the U.S. Central Intelligence Agency informed the President that it had no evidence that the USSR was creating a fusion weapon [6, p. 11].

7. The radiation implosion principle and RDS-37

The RDS -37 and subsequent generations of thermonuclear charges stemmed from fundamental scientific concepts of high energy density physics.

The principle of radiation implosion assumes:

• the predominant proportion of the energy of the explosion of the nuclear charge (the primary module) is generated in the form of X-ray radiation;

• the energy of the X-ray radiation is transported to the fusion module;

• the implosion of the fusion module using the energy of the 'delivered' X-ray radiation.

The possibility of more efficient compression of nuclear material than provided by the blast of a chemical explosive was discussed even in the early 1950s. This idea was first formulated in the general form as an idea of nuclear explosions of one or more charges to compress the nuclear fuel placed in an isolated module which is spatially separated from the primary source (sources) of the nuclear explosion.

In January 1954, Ya B Zeldovich and A D Sakharov considered in detail a device layout which incorporated the principle of a two-stage nuclear charge. From the outset, a number of questions were formulated concerning the feasibility of the realization of this idea; the questions can be separated into two groups.

The first group of questions dealt with the very concept of 'nuclear implosion'. The operational diagram for the nuclear charge was by that time well-studied: it assumed compression of a nuclear material (or fission and fusion materials, as in the PDS-6s) by spherical explosion of chemical explosives, in which the spherical symmetry of the implosion was dictated by the initial spherically symmetric detonation of the explosive. It was apparent that in a heterogeneous structure composed of a primary source (or sources) and a compressible secondary module there were no analogous initial opportunities to maintain the spherically symmetric 'nuclear implosion'. This issue was closely linked to other issues: what is now the carrier of the explosive energy of the original source, and how is this energy transported to the secondary module?

The second group of issues stemmed from the question: what is going to play the role of the secondary module impacted by the nuclear implosion.

Initially, it was assumed that the energy of a nuclear explosion of the primary source in a two-stage charge would be transported by the flux of the products of explosion and the shock wave created by them and propagating through the heterogeneous structure of the charge. In January 1954, Zeldovich and Sakharov analyzed this approach. It was decided to choose an analog of the inner element of the RDS-6s charge for the basic physical element of the secondary module, i.e. the 'layered' spherical configuration of the system.

It should be noted that from the standpoint of computational capabilities available at the time, it was an extremely complicated system. The velocities of propagation of shock waves around and inside the module not differing too much, the main problem was how to maintain a nearly spherically symmetric mode of compression of the secondary module in a charge of this complexity.

After a few months of working on the project, a solution to this problem was found — the team developed the so-called encapsulation principle: the energy of the primary module was transported by X-rays, while the directionality of energy transfer was provided by placing the primary and secondary modules in a unifying shell (as in the case of hydrodynamic implosion applied in the January project) possessing high reflectivity for X-rays; measures were also taken that helped transfer X-ray radiation within the charge in the required direction.

Sakharov gave this description of how the idea of radiation implosion was born at KB-11 (he called it the 'third idea') [8]:

"It appears that the 'third idea' was hit upon simultaneously by several members of our theoretical departments. I was one of them. As far as I can remember, I already understood the main physical and mathematical aspects of the third idea at the early stage. In view of this, and also because of the reputation I enjoyed by that time, my role in selecting the third idea and in its subsequent implementation could have been one of the decisive factors. There is no doubt that the roles of Zeldovich, Trutnev, and some others were also very important; perhaps they understood and foresaw the prospects and challenges of the third idea just as clearly as I did."

On 8 July 1955, a report emerged, "An experimental device for testing the encapsulation principle (computational and theoretical work)" which summarized the material needed for the determination of the basic physical processes occurring in the RDS-37 and its physical parameters, including the anticipated energy release.

In the Introduction to this report, we read: "...the encapsulation principle was being developed in theory sectors since 1950. In early 1954, the first successes were achieved, namely, it became clear that it was, in principle, possible to attain symmetrical compression of the hydrogen bomb ('main gadget') via radiative heat exchange between the additional ('primary') gadget and a layer of light substance ('plastering') surrounding the main gadget.

The most important role in gadgets using the encapsulation principle is played by a set of processes that had never been tested experimentally nor studied theoretically:

(1) Radiative heat exchange in a cavity of a complex shape.

(2) Penetration of heat into 'plastering' and into 'housing', accompanied by expansion into a vacuum.

According to calculations, the proposed system is robust. Its power was estimated to be in the range of 600–1400 thousand tons TNT.

The development of the encapsulation principle is one of the brilliant examples of a team creativity. Some people generated ideas (very many ideas were needed, and some were advanced independently by several authors). Others were stronger in the realm of computation methods and in clarifying the importance of a number of physical processes" [9].

To quote from the conclusions of I E Tamm's commission of experts of 1 July 1955: "The commission notes that KB-11 and OPM [1] have completed a great deal of work on studying the new physical principles that lie at the foundation of the design of hydrogen bombs with atomic compression" [9].

The testing of RDS-37 was supervised by I V Kurchatov. Taking part in the preparation of the gadget for testing and in the test itself were the leadership of the USSR Ministry of Defense: Deputy Minister of Defense A M Vasilevskii, M I Nedelin, V A Bolyatko, Vice Chairman of the USSR CM — Minister of the Ministry of Medium Machine Building (MinSredMash) A P Zavenyagin with a large group of top administrators of MSM, and heads of R&D institutes where methods of measurements were developed.

Present at the tests was a large group of brilliant mathematicians: M V Keldysh, I M Gelfand, S K Godunov, V F D'yachenko, O V Lokutsievskii, A A Samarskii, and A N Tikhonov.

The summarized materials on the results of testing the RDS-37 gadget bear the signatures of I V Kurchatov, Yu B Khariton, N N Semenov, A D Sakharov, Ya B Zeldovich, and M A Sadovskii.

Having considered the results of testing the RDS-37 at its meeting of 24 November 1955, the commission noted the following:

• the design of the hydrogen bomb, based on a novel principle, has been successfully tested;

• it is necessary to continue detailed studies of the processes proceeding in explosions of bombs of this type;

• further development of hydrogen bombs should be conducted on the basis of a broad application of the principles chosen as the foundation of the RDS-37 bomb.

The successful testing of the first thermonuclear device based on the principle of atomic compression made it possible to start large-scale development of thermonuclear weapons.

[1] Division of Applied Mathematics (OPM in *Russ. abbr.*) of the Institute of Mathematics of the AS USSR. (*Editor's note.*)

The creation of the RDS-37 charge closed the breach in addressing the problem of Soviet thermonuclear weapons, and the charge itself became the prototype for all subsequent two-stage thermonuclear devices in the USSR.

References [2]

1. Ryabev L D (Gen. Ed.), Kudinova L I (Comp.) *Atomnyi Proekt SSSR. Dokumenty i Materialy* (Atomic Project USSR. Documents and Materials) Vol. 1 *1938–1945* Pt. 1 (Moscow: Fizmatlit, 1998) pp. 306, 307
2. "U istokov sovetskogo atomnogo proekta: rol' razvedki. 1941–1946" ("At the root of the Soviet atomic project: the role of intelligence. 1941–1946") *Voprosy Istorii Estestvoznaniya Tekh.* (3) 116,117 (1992)
3. Khariton Yu B "Vstuplenie SSSR v atomnuyu eru" ("USSR enters atomic age"), in Andryushin I A, Chernyshev A K *60 Let Mira, 1949–2009. K Shestidesyatiletiyu Ispytaniya Pervoi Sovetskoi Atomnoi Bomby* (60 Years of Peace, 1949–2009. 60 Years Anniversary of Testing the First Soviet Atomic Bomb) (Sarov: RFYaTs–VNIIEF, 2009) p. 3
4. Ryabev L I (Gen. Ed.), Goncharov G A (Exec. Ed.) *Atomnyi Proekt SSSR. Dokumenty i Materialy* (Atomic Project USSR. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 2 (Sarov: Izd. RFYaTs–VNIIEF, 2000) pp. 491–494
5. Andryushin I A, Chernyshev A K, Yudin Yu A *Ukroshchenie Yadra. Stranitsy Istorii Yadernogo Oruzhiya i Yadernoi Infrastruktury SSSR* (Taming of the Nucleus. Pages from the History of Nuclear Weapons and Nuclear Infrastructure in the USSR) (Sarov, Saransk: Tip. "Krasnyi Oktyabr", 2003)
6. Andryushin I A, Ilkaev R I, Chernyshev A K *'Sloika' Sakharova. Put' Geniya* (Sakharov's 'Sloika'. Path of the Genius) (Sarov: FGUP RFYaTs–VNIIEF, 2011)
7. Ilkaev R I *Phys. Usp.* **55** 183 (2012) [*Usp. Fiz. Nauk* **182** 195 (2012)]
8. Sakharov A D *Nauchnye Trudy* (Scientific Works) (Editorial Board: L V Keldysh (Chair) et al.) (Moscow: OTF FIAN — TsentrKom, 1995)
9. Andryushin I A, Ilkaev R I, Chernyshev A K *Reshayushchii Shag k Miru. Vodorodnaya Bomba s Atomnym Obzhatiem RDS-37* (A Decisive Step Towards Peace. The Hydrogen Bomb with Atomic Compression RDS-37) (Sarov: FGUP RFYaTs–VNIIEF, 2010) pp. 66, 77
10. Khariton Yu B, Adamskii V B, Smirnov Yu N *Phys. Usp.* **39** 185 (1996) [*Usp. Fiz. Nauk* **166** 201 (1996)]
11. Romanov Yu A *Phys. Usp.* **39** 179 (1996) [*Usp. Fiz. Nauk* **166** 195 (1996)]
12. Goncharov G A *Phys. Usp.* **39** 1033 (1996) [*Usp. Fiz. Nauk* **166** 1095 (1996)]
13. Kadomtsev B B *Phys. Usp.* **39** 419 (1996) [*Usp. Fiz. Nauk* **166** 449 (1996)]
14. Goncharov G A *Phys. Usp.* **40** 859 (1997) [*Usp. Fiz. Nauk* **167** 903 (1997)]
15. Krivonosov Yu I *Phys. Usp.* **43** 949 (2000) [*Usp. Fiz. Nauk* **170** 1021 (2000)]
16. Goncharov G A, Ryabev L D *Phys. Usp.* **44** 71 (2001) [*Usp. Fiz. Nauk* **171** 79 (2001)]
17. Goncharov G A *Phys. Usp.* **44** 859 (2001) [*Usp. Fiz. Nauk* **171** 902 (2001)]
18. Shafranov V D, Bondarenko B D, Goncharov G A, Lavrent'ev O A, Sakharov A D *Phys. Usp.* **44** 835 (2001) [*Usp. Fiz. Nauk* **171** 877 (2001)]
19. Kiselev G V *Phys. Usp.* **48** 1251 (2005) [*Usp. Fiz. Nauk* **175** 1343 2005)]
20. Goncharov G A *Phys. Usp.* **48** 1187 (2005) [*Usp. Fiz. Nauk* **175** 1243 (2005)]
21. Kiselev G V, Konev V N *Phys. Usp.* **50** 1259 (2007) [*Usp. Fiz. Nauk* **177** 1361 (2007)]
22. Kiselev G V *Phys. Usp.* **51** 911 (2008) [*Usp. Fiz. Nauk* **178** 947 (2008)]
23. Mirnov S V *Phys. Usp.* **52** 725 (2009) [*Usp. Fiz. Nauk* **179** 767 (2009)]
24. Ilkaev R I *Phys. Usp.* **54** 387 (2011) [*Usp. Fiz. Nauk* **181** 405 (2011)]
25. Azizov E A *Phys. Usp.* **55** 190 (2012) [*Usp. Fiz. Nauk* **182** 202 (2012)]

[2] For more on the history of building the Soviet nuclear shield and the peaceful use of atomic energy, see also Refs [10–25]. (*Editor's note.*)

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History of the Universe History

A M Cherepashchuk

1. Introduction

This review deals with the development of our concepts on the structure and evolution of the Universe. Two revolutions in astronomy will be considered: the transition from the geocentric to heliocentric model, and from the static Universe to the nonstationary expanding Universe, including the early inflation phase. Presently, we are on the eve of the third revolution in astronomy, which is related to the discovery of accelerating expansion of the Universe and the realization of the fact that baryonic matter constitutes only 4% of the total matter density in the Universe. The outstanding achievements of modern cosmology are striking (see, e.g., monographs [1–3]).

It is worth getting back to the basics of astronomy to follow up the development of the modern cosmological model. This is especially important because in recent years a wicked principle, 'onward to the past', is being established in our country. Under the slogan of getting back to old traditions, to the historical roots of our people, paganism and obscurantism are resurging. The materialistic vision of the world is being attacked. Natural sciences disciplines are emasculated from school educational programs. In particular, for more than a decade astronomy has not been taught as a separate subject in Russian schools. A wave of militant obscurantism has engulfed television, radio and other mass media. The natural result is ensuing: according to public opinion polls carried out by The All-Russian Public Opinion Research Center (WCIOM), the proportion of the Russian people who think that the Sun orbits Earth and not vice versa increased in 2007–2011 from 29% to 33% (wciom.ru/index.php?d = 459&uid = 111345). So, one third of the Russian population shares the medieval point of view and, sadly, the number of these people is increasing. Therefore, it seems timely and proper to write the present review.

2. Astronomy — the oldest science

The first signs of early astronomical science go back to 700–800 BCE [4–6]. As a rule, they exhibit points of similarity with observational astronomical areas, astronomical drawings, and images of lunar calendars on the walls of caves. For example, ancient Maya inscribed astronomical cartoons on the walls of caves more than six thousand years ago [7, 8]. Apparently, there are traces of human astronomical practices as early as 2000 BCE: for example, a rod made of mammoth bone was found near Achinsk (Russia), which had the

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