ISTC Project # 1763p

Manuscript on the History of the Soviet Nuclear Weapons and Nuclear Infrastructure

(Technical Report on Tasks A-1 and A-2)

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Abstract

The scope of activities under ISTC Project #1763p includes compiling a manuscript on the history of the Soviet nuclear weapons and nuclear infrastructure. The manuscript will review some results of 50 years of nuclear weapons development and discuss some aspects of peaceful uses of nuclear weapons. The manuscript is consistent with the policy of Russia's Minatom aimed at publicizing accomplishments of the country's atomic science and industry. This technical report presents the results of Task A-1/A-2 activities as specified in the Project Work Plan.

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Milestones of the Soviet Atomic Industry Development

The below milestone chronology of the Soviet atomic industry development highlights events starting from 1938, even though, of course, there were a number of fundamental events in the development of the Soviet nuclear science and technology that took place earlier. The important organizational events of this pre-history include, in particular

September 24, 1918 - *The Institute of Roentgenology and Radiology incorporating a department of physics and engineering under the leadership of Professor A.F.Ioffe is established*

December 15, 1918 - *The State Optics Institute in Petrograd headed by Member of Academy D.S.Rozhdestvensky is established*

Late 1918 - *The Central Chemical Laboratory in Moscow is established, which is transformed in 1931 into the Institute of Physics and Chemistry under the direction Member of Academy of A.N.Bakh*

January 21, 1920 - *First Meeting of the Atomic Board attended by A.F.Ioffe, D.S.Rozhdestvensky, A.N.Krylov and other outstanding scientists is convened*

April 15, 1921 - *The Radium Laboratory directed by V.G.Khlopin of the Academy of Sciences is established*

Late 1921 - *I.Ya.Bashilov develops and implements a technology to process uranium ore extracted from the Tyuyamuyunsk deposit to manufacture radium and uranium containing products*

January 1, 1922 - *The State Institute of Roentgenology and Radiology is transformed into three independent research institutes:*

- *Institute of Roentgenology and Radiology directed by M.I.Nemenov;*
- *Institute of Physics and Engineering (LFTI) under the direction of A.F.Ioffe;*
- *Radium Institute headed by V.I.Vernadsky*

March 1, 1923 - *The State Committee for Labor and Defense adopts a resolution on uranium mining and accounting*

1928 - *The Ukrainian Institute of Physics and Engineering (UFTI), Kharkiv headed by I.V.Obreimov is established*

1931 - *The Institute of Chemical Physics in Leningrad under the direction of N.N.Semenov is established*

1931 - *The State Research Institute of Rare Metals (Giredmet) headed by V.I.Glebova is established based on the Institute of Applied Mineralogy*

1932 - *D.D.Ivanenko puts forward a hypothesis that nuclei consist of protons and neutrons*

1933 - *A commission in charge of atomic nucleus studies at the Soviet Academy of Sciences (AN SSSR) is created including A.F.Ioffe (Chairman), S.E.Frish, I.V.Kurchatov, A.I.Leipunsky and A.V.Mysovsky*

September 24 through 30, 1933 - *First All-Union Conference on Nuclear Physics takes place in Leningrad*

1934 - *P.A.Cherenkov discovers Cherenkov radiation*

1934 - *Heavy water is first produced in the USSR by A.I.Brodsky (Institute of Physical Chemistry of the Ukrainian Academy of Sciences)*

December 28, 1934 - *The Institute for Physical Problems, Moscow directed by P.L.Kapitza is established*

1935 - *I.V.Kurchatov and his team discover nuclear isomerism*

September 20 through 26, 1936 - *Second All-Union Conference on Nuclear Physics convenes in Moscow*

1937 - *The Radium Institute generates an accelerated proton beam using Europe's first cyclotron*

Summer 1938 - *V.G.Khlopin, Radium Institute Director drafts proposals on atomic nucleus problem development by the AN SSSR Institutes for the third five-year plan*

October 1 through 6, 1938 - *Third All-Union Conference on Nuclear Physics convenes in Leningrad*

Late 1938 - *S.I.Vavilov, Physical Institute Director draws up proposals on atomic nucleus research arrangement in the Institutes of the AN SSSR*

November 25, 1938 - *The Presidium of the AN SSSR passes a resolution on atomic nucleus research and establishment of a permanent Commission for Atomic Nucleus of the Academy's Department of Physics and Mathematics including S.I.Vavilov*

(Chairman), A.F.Ioffe, I.M.Frank, A.I.Alikhanov, I.V.Kurchatov and V.I.Veksler. In June 1940, the Commission involves V.G.Khlopin and I.I.Gurevich

March 7, 1939 - *M.G.Pervukhin suggests that atomic nucleus research activities be concentrated in the Kharkiv Institute of Physics and Engineering*

November 15 through 20, 1939 - *Fourth All-Union Conference on Nuclear Physics takes place in Kharkiv*

April 16 through 17, 1940 - *First All-Union Meeting on Isotopic Chemistry is convened. The conference discusses the plans for heavy water production at the Chirchik Electrolysis Plant*

May 1940 - *K.A.Petrzhak and G.N.Flerov discover spontaneous fission of uranium*

July 12, 1940 - *V.I.Vernadsky, A.E.Fersman and V.G.Khlopin suggest a plan for the development of atomic power applications*

July 1940 - *A.P.Vinogradov suggests that uranium hexafluoride be used for uranium isotope separation*

July 30, 1940 - *The Uranium Commission is established to coordinate and guide uranium research by the AN SSSR including V.G.Khlopin (Chairman), V.I.Vernadsky (Deputy Chairman), A.F.Ioffe (Deputy Chairman), A.E.Fersman, S.I.Vavilov, P.P.Lazarev, A.N.Frumkin, L.I.Mandelstam, G.M.Krzhizhanovsky, P.L.Kapitza, I.V.Kurchatov, D.I.Shcherbakov, A.P.Vinogradov and Yu.B.Khariton*

August 23, 1940 - *A.P.Vinogradov suggests that new volatile uranium compounds (other than* UF_6*) should be sought in order to solve the problem of uranium isotope separation*

August 29, 1940 - *I.V.Kurchatov, Yu.B.Khariton, L.I.Rusinov and G.N.Flerov propose using energy from self-sustained uranium fission*

September 5, 1940 - *A.E.Fersman suggests that uranium ore exploration and mining efforts be sped up*

October 15, 1940 - *The Uranium Commission draws up a plan for research and geological survey activities in 1940-1941. The key tasks include*

- *chain reaction feasibility study as applied to natural uranium;*
- *specification of physical data needed for evaluation of U-235-involving chain reaction propagation;*

- *study of various approaches to isotope separation and applicability of these for uranium;*
- *study of possible ways to produce volatile organic uranium compounds;*
- *evaluation of raw uranium sources and creation of uranium stocks*

November 30, 1940 - *A.E.Fersman reports on the results of uranium ore exploration in the Central Asia*

Late 1940 - *F.F.Lange, V.A.Maslov and V.S.Shpinel put forward a concept of centrifuge uranium isotope separation*

Early 1941 - *F.F.Lange and V.A.Maslov propose improvement of the centrifuge uranium separation method*

April 15, 1941 - *The Soviet Council of People's Commissars (SNK SSSR) passes a resolution on building a high-power cyclotron in Moscow*

June 22, 1941 - *Nazi Germany invades the Soviet Union. The Great Patriotic War begins*

October 1941 - *The Soviet People's Commissariat of Internal Affairs (NKVD SSSR) receives first intelligence on the uranium project of Great Britain*

Summer 1942 - *G.N.Flerov proposes nuclear explosive device constructing*

September 28, 1942 - *The State Defense Committee (GKO) issues a resolution on setting up uranium-related activities, which gives rise to the Soviet atomic project. The resolution calls for establishing a Special Laboratory for Atomic Nucleus of the AN USSR (Laboratory 2) to coordinate the atomic project*

November 27, 1942 - *GKO issues a resolution on uranium production*

November 27, 1942 - *I.V.Kurchatov draws up an internal memorandum for V.M.Molotov analyzing the intelligence on Great Britain's atomic project progress and containing proposals for the Soviet atomic weapons development*

January 15, 1943 - *V.G.Khlopin proposes arranging activities on the atomic problem*

January 25, 1943 - *I.V.Kurchatov and A.I.Alikhanov draw up the first work plan of the Special Laboratory for 1943*

February 11, 1943 - *GKO's uranium project resolution appoints M.G.Pervukhin and S.V.Kaftanov uranium project managers. Scientific project leadership is entrusted to I.V.Kurchatov*

March 10, 1943 - *I.V.Kurchatov is appointed Head of Laboratory 2 of the AN SSSR (now the Russian Scientific Center - Kurchatov Institute, Moscow), the scientific center of the atomic project*

1943 - *I.V.Kurchatov systematically analyzes the intelligence on the atomic projects of the U.S. and Great Britain provided by the NKVD SSSR and develops proposals addressed to M.G.Pervukhin on the development of the Soviet atomic project*

July 30, 1943 - *The GKO issues a resolution on launching geological survey and production of uranium*

December 16, 1943 - *The Commission for Atomic Nucleus of the Academy's Department of Physics and Mathematics is transformed into the Cosmic Ray Commission*

March 19, 1944 - *I.V.Kurchatov formulates engineering requirements to the chemical purity of uranium materials supplied to Laboratory 2*

May 15, 1944 - *Commercial production of highly pure graphite parts is launched*

June 25, 1944 - *The cyclotron at Laboratory 2 is commissioned*

November 1944 - *Uranium metal production technology development is initiated*

November 21, 1944 - *A group of Soviet experts is sent to Bulgaria to estimate uranium ore deposits*

December 8, 1944 - *GKO issues a resolution on entrusting uranium ore production and processing to the NKVD SSSR and establishing a Special Directorate*

Late 1944 - *Research Institute 9 (NII 9) directed by V.B.Shevchenko is established within the NKVD (now the Bochvar Research Institute of Inorganic Materials (VNIINM), Moscow) to develop production technologies for uranium metal, its special compounds and plutonium metal*

January 27, 1945 - *The GKO resolves to conduct negotiations with the Government of Bulgaria on establishing a Soviet-Bulgarian corporation for uranium ore exploration and mining*

May 9, 1945 - *A group of Soviet specialists headed by A.P.Zavenyagin is sent to Germany to find and accept documents related to the German uranium activities. The most important accomplishment of this effort is that about a hundred tons of uranium concentrate have been found and brought to the USSR*

May 15, 1945 - *The GKO issues a resolution establishing Mining Complex 6 under the direction of B.N.Chirkov (Leninabad Mining Complex) to produce and process uranium ores in the Middle Asia*

July 16, 1945 - *An atomic bomb is first tested by the United States*

August 6, 1945 - *An atomic bomb is fist used for military purposes. The U.S. drops the uranium bomb on Hiroshima, Japan*

August 20, 1945 - *The GKO resolves to establish a Special Committee of the GKO to guide all activities in the area of atomic power utilization, including L.P.Beria as Chairman, G.M.Malenkov, N.A.Voznesensky, B.L.Vannikov, A.P.Zavenyagin, I.V.Kurchatov, P.L.Kapitza, M.G.Pervukhin and V.A.Makhnev. A Technical Board of the Special Committee is established including B.L.Vannikov as Chairman, A.I.Alikhanov, I.N.Voznesensky, A.P.Zavenyagin, A.F.Ioffe, P.L.Kapitza, I.K.Kikoin, I.V.Kurchatov, V.A.Makhnev, Yu.B.Khariton and V.G.Khlopin. At the Technical Board there are established Commissions for Electromagnetic Uranium Separation (headed by A.F.Ioffe), for Heavy Water Production (headed by P.L.Kapitza), for Plutonium Research (headed by V.G.Khlopin), for Analytical Chemistry (headed by A.P.Vinogradov) and for Operational Safety (headed by V.V.Parin)*

August 30, 1945 - *The SNK SSSR issues a resolution establishing the First Main Directorate (PGU) of the SNK SSSR (including B.L.Vannikov as Head, A.P.Zavenyagin, P.Ya.Antropov, N.A.Borisov, A.G.Kasatkin and P.Ya.Meshik as Deputy Heads and A.N.Komarovsky, G.P.Korsakov and S.E.Egorov as Board Members)*

August 30, 1945 - *The GKO issues a resolution on incorporating into the PGU of Factory 12 (now the "Machine Building Works" Public Joint-Stock Company, Elektrostal) under the direction of S.A.Nevstruyev to produce uranium blocks and uranium metal*

September 4, 1945 - *The GKO issues a resolution on incorporating into the PGU of the leading design institution, State Special Design Institute (GSPI-11, now the*

Leningrad All-Russian Research and Design Institute of Power Engineering, VNIPIET) directed by A.I.Gutov

September 4, 1945 - *The GKO resolves to on arrange heavy water production*

September 14, 1945 - *The SNK SSSR issues a resolution on incorporating into the PGU of Factory 48 (now MOLNIA Machine Building Works, Moscow) headed by P.A.Rastegayev to manufacture special equipment*

September 1945 - *Joint activities are initiated to explore uranium deposits and mine uranium in the Eastern Germany*

October 8, 1945 - *The Technical Board of the Special Committee issues a resolution establishing Laboratory 3 (now the Moscow Institute of Theoretical and Experimental Physics, ITEF) under the direction of A.I.Alikhanov to design heavy water reactors*

October 17, 1945 - *An agreement is signed with the Government of Bulgaria on uranium ore exploration and production*

November 23, 1945 - *An agreement is signed with the Government of Czechoslovakia on uranium ore production and delivery from the Yakhim deposit*

December 1, 1945 - *The SNK SSSR issues a resolution establishing Complex 817 (now the MAYAK Chemical Complex, Oziorsk) including Plant A (industrial reactor), Plant B (radiochemical plant) and Plant V (metallurgical plant for uranium production) directed by P.T.Bystrov, E.P.Slavsky, B.G.Muzrukov, I.V.Kurchatov, Scientific Leader of the Complex and N.A.Dollezhal, Chief Designer*

December 1, 1945 - *The SNK SSSR issues a resolution establishing Complex 813 (now the Ural Electromechanical Plant, Novouralsk) headed by A.I.Churin, Director, I.K.Kikoin, Scientific Leader and I.N.Voznesensky, Chief Designer for gaseous-diffusion uranium isotope separation*

December 10, 1945 - *The SNK SSSR issues a resolution establishing an Engineering Board of the Special Committee headed by M.G.Pervukhin. The Board includes six sections:*

- *Section 1 for designing and constructing factories of Plutonium Complex 817 (M.G.Pervukhin, I.V.Kurchatov);*
- *Section 2 for designing and constructing factories of Gaseous-Diffusion Uranium Isotope Separation Complex 813 (V.A.Malyshev, I.K.Kikoin);*

- *Section 3 for designing and constructing facilities of Electromagnetic Uranium Isotope Separation Complex 814 (G.V.Aleksenko, L.A.Artsimovich);*
- *Section 4 for designing isotope separation facilities (A.V.Kasatkin, M.O.Kornfeld);*
- *Section 5 for designing and constructing mining works (A.P.Zavenyagin, N.F.Pravdyuk);*
- *Section 6 for instrument making (N.A.Borisov).*

December 17, 1945 - *The SNK SSSR issues a resolution establishing Laboratory 2 of the PGU headed by F.F.Lange to develop a centrifuge uranium isotope separation method*

December 19, 1945 - *The SNK SSSR issues a resolution establishing Laboratory V within the NKVD under the direction of L.S.Buyanov (now RFNC-FEI, Obninsk) to develop new reactor designs*

December 27, 1945 - *The SNK SSSR issues a resolution establishing OKB Elektrosila (now NPO Elektrofizika) under the direction of D.V.Efremov, Head and L.A.Artsimovich, Scientific Leader to devise equipment for electromagnetic uranium separation*

December 27, 1945 - *The SNK SSSR issues a resolution establishing OKB LKZ (Leningrad Kirov's Factory) and OKB GMZ (Gorky Machine Building Works) to design facilities for gaseous-diffusion uranium separation (OKB LZK Chief Designer is S.A.Arkin; OKB GMZ Chief Designer is A.I.Savin)*

Late 1945 - *100 tons of raw uranium are delivered to Factory 12 from Germany*

January 28, 1946 - *The SNK SSSR issues a resolution establishing OKB GIDROPRESS, Podolsk headed by B.M.Sholkovich to design nuclear reactors*

January 29, 1946 - *The UN's General Assembly resolves to establish the UN Nuclear Energy Commission*

March 1946 - *Development of two industrial reactor designs is initiated (Chief Designer for Vertical Reactor Setup is N.A.Dollezhal, Chief Designer for Horizontal Reactor Setup is B.M.Sholkovich)*

March 21, 1946 - *The Soviet Council of Ministers (SM SSSR) issues a resolution instituting special prizes for scientific discoveries and engineering accomplishments in the area of atomic power utilization*

April 9, 1946 - *The Soviet Government issues a resolution establishing KB-11 (now RFNC-VNIIEF, Arzamas-16 now Sarov) headed by P.M.Zernov, Director and Yu.B.Khariton, Chief Designer and Scientific Leader, which becomes the center of nuclear weapons development*

April 9, 1946 - *The SM SSSR issues a resolution on integrating the Technical Board and Scientific and Technical Board of the Special Committee into the Scientific and Technical Board of the PGU*

April 15 1946 - *First meeting of the Scientific and Technical Board of the PGU including B.L.Vannikov as Chairman and I.V.Kurchatov, A.I.Leipunsky, M.G.Pervukhin, B.S.Pozdnyakov, N.N.Semenov, Y.B.Khariton, V.G.Khlopin, A.I.Alikhanov and A.F.Ioffe as Board Members takes place*

April 1946 - *The Soviet Government issues a resolution entrusting the Institute of Chemical Physics with the task to develop nuclear explosion diagnostic means (Scientific Project Leader is M.A.Sadovsky)*

April 24, 1946 - *The SM SSSR issues a resolution on placing the Podolsk Pilot Plant (now the NPO Luch) under the control of the PGU*

June 19, 1946 - *The USSR submits a proposal to the UN Atomic Energy Commission on prohibiting atomic weapons production and utilization*

June 21, 1946 - *The SM SSSR issues a resolution on the commencement in KB-11 of the development of two atomic bomb designs based on plutonium and uranium-235. According to the resolution, the air bombs based on plutonium and uranium-235 are to be developed and submitted for state tests by March 1, 1948 and January 1, 1949, respectively*

July 1, 1946 - *Yu.B.Khariton draws up a tactical and technical order for atomic bomb development*

July 27, 1946 - *The SM SSSR issues a resolution establishing Mining Complex 7 (now GAO Silmet) within the PGU to industrially produce Baltic uranium-containing slates*

December 9, 1946 - *Factory 544 (now the GP Chepetsk Mechanical Works, Glazov) redirected to uranium metal production is placed under the control of the PGU*

December 16, 1946 - *The Radiation Laboratory (now the Institute of Biophysics, Pushchino) headed by G.M.Frank is established to study radiation effects on humans*

December 16, 1946 - *PGU Scientific Secretary B.S.Pozdnyakov formulates proposals on peaceful applications of atomic power*

December 25, 1946 - *First nuclear reactor F-1 at Laboratory 2 is commissioned*

1946 - *Radium Institute develops a technology for irradiated reactor-grade uranium processing and plutonium separation (V.G.Khlopin as Scientific Leader)*

April 21, 1947 - *The Soviet Government resolves to establish a testing ground (Mountain Station, Training Site 2, Semipalatinsk Test Site) under the direction of P.M.Rozhanovich, Head and M.A.Sadovsky, Scientific Leader for atomic bomb tests*

19 June 1947 - *The SM SSSR issues a directive to start the project at KB-11 and establish a Scientific and Technical Board of Laboratory 2 to discuss issues associated with the atomic bomb development including I.V.Kurchatov as Chairman, Yu.B.Khariton as Vice-Chairman, N.N.Semenov, K.I.Shchelkin, A.S.Aleksandrov, P.M.Zernov as Board Members and A.P.Aleksandrov, I.K.Kikoin, Ya.B.Zeldovich, A.A.Bochvar, A.S.Zaimovsky, B.A.Nikitin and K.V.Selikhov as Board Experts. Head of Radiochemical Department of Complex 817 B.A.Nikitin is appointed manager of the project aimed at production of polonium and its compounds*

August 1947 - *The Soviet Government issues a resolution establishing a Special Directorate within the Ministry for Public Health of the USSR headed by A.I.Burnazyan in charge of providing special medical services to the atomic industry employees*

August 1947 - *The Soviet Government issues a resolution establishing Air Force Test Site 71 for air tests of atomic bomb mock-ups*

August 14, 1947 - *The SM SSSR issues a resolution on constructing in the Ukraine of Factory 906 (now the GP Dnepr Chemical Factory) to process uranium ores from the Pervomaisk and Zheltorechensk deposits*

September 15, 1947 - *An agreement with the Government of Poland is signed on uranium ore exploration and production*

Late 1947 - *The Soviet Government issues a resolution establishing Factory 418 (now the Elektrokhimpribor Works, Sverdlowsk-45, now Lesnoy) headed by D.E.Vasiliev, Director and L.A.Artsimovich, Scientific Leader for electromagnetic isotope separation*

1947 - *KB-11 divisions start to form*

February 8, 1948 - *The Soviet Government issues a resolution on creating GSPI-12 under the direction of F.Z.Shiryayev to become the second design institute within the atomic industry*

June 10, 1948 - *The SM SSSR resolves to supplement the schedule of KB-11 with a task to theoretically and experimentally verify the data on the design feasibility of three new types of atomic bombs before January 1, 1949:*

- *RDS-3 - implosion-based 'solid' atomic bomb containing a combination of Pu-239 and U-235;*
- *RDS-4 - implosion-based enhanced-design atomic bomb containing Pu-239;*
- *RDS-5 - implosion-based enhanced-design atomic bomb containing a combination of Pu-239 and U-235;*

After the development of the RDS-2 U-235-based atomic bomb was canceled, these nuclear devices were renamed.

This resolution also charges KB-11 with a task of theoretical and experimental verification of the data on the design feasibility of the RDS-6 hydrogen bomb by June 1, 1949

June 10, 1948 - *Resolution of the SM SSSR on strengthening KB-11 by engaging leading design specialists confirms appointment of K.L.Shchepin as First Deputy Chief Designer, and V.L.Alferov and N.L.Dukhov as Deputy Chief Designers*

June 15, 1948 - *Industrial reactor (Plant A Complex 817) is brought to its rated capacity*

August 15, 1948 - *The SM SSSR issues a resolution on considering nuclear weapons defense capabilities involving high-energy neutral and charged particles flows (Institute of Chemical Physics, Institute of Physics, Laboratory 2)*

September 28, 1948 - *The SM SSSR issues a resolution on constructing in Novosibirsk of the Uranium Metallurgy and Metal Processing Factory (now the Novosibirsk Chemical Concentrate Works Public Joint-Stock Company)*

October 4, 1948 - *The SM SSSR issues a resolution establishing the Ust'kamenogorsk Zinc Factory (now the PO Ul'binsky Mechanical Works)*

November 1948 - *A.I.Leipunsky proposes a fast neutron reactor concept*

December 22, 1948 - *Radiochemical Plant B of Complex 817 is commissioned*

Late 1948 - *A pilot batch of highly enriched uranium (75% of U-235) is produced at Complex 813*

Late 1948 - *Factory 418 for electromagnetic isotope separation is commissioned*

1948 - *NII-9 tests a technology for large-scale plutonium production from F-1 pilot reactor's uranium fuel*

February 26, 1949 - *First batch of plutonium separated at Plant B of Complex 817 is delivered to Plant V*

March 3, 1949 - *The Soviet Government issues a resolution establishing the first large-scale atomic weapons production (now the Avangard Electromechanical Plant, Sarov)*

April 1949 - *Plant V of Complex 817 starts production of uranium alloy parts according to the technology developed at NII-9 (Scientific Project Managers are A.S.Zaimovsky and A.A.Bochvar)*

April 11, 1949 - *A special team is created at KB-11 in charge of arranging tests of the first atomic bomb RDS-1*

April 1949 - *First research reactor with natural uranium and heavy water is put into operation (Heat Engineering Laboratory of the AN SSSR, ITEF)*

June 1949 - *Complex 813 industrially produces highly enriched uranium (75% of U-235)*

July 26, 1949 - *Preparation of the testing ground for the RDS-1 atomic bomb tests is completed*

27 July 1949 - *The Governmental Commission headed by M.G.Pervukhin starts its work at the testing ground*

August 8, 1949 - *Plutonium parts for the first atomic bomb fabricated at Plant V of Complex 817 are delivered to KB-11*

August 22, 1949 - *Final rehearsal of the first atomic bomb tests takes place at the testing ground*

August 26, 1949 - *The Special Committee issues a resolution on testing the RDS-1 atomic bomb*

August 29, 1949 - *Tests of the RDS-1, the first atomic bomb, take place at 7 a.m. local time (4 a.m. Moscow time)*

Fall 1949 - *Construction of Factory 816 in Tomsk-7 (now the Siberian Chemical Complex, Seversk) is started to produce weapon-grade plutonium and highly enriched uranium*

October 28, 1949 - *L.P.Beria reports the results of the first atomic bomb tests to I.V.Stalin*

October 29, 1949 - *The SM SSSR issues a resolution and the Presidium of the Supreme Soviet of the USSR issues decrees on awards and prizes for outstanding discoveries and technical achievements in the area of atomic power utilization, according to which many specialists who contributed to coping with the task of the first Soviet atomic bomb development were awarded Stalin Prizes of different categories and USSR Orders*

December 27, 1949 - *The SM SSSR resolves to establish the Second Main Directorate (VGU) of the SM SSSR based on the Mining Directorate of the PGU in order to concentrate uranium ore production and processing activities (headed by P.Ya.Antropov)*

February 14, 1950 - *The Soviet Government issues a resolution on separating from KB-11 of Factory 551 under the direction of V.V.Dubitsky for serial atomic bomb production*

May 16, 1950 - *The Soviet Government issues a resolution on constructing a nuclear power station at Laboratory V, Obninsk, being the first applied project in the area of atomic power utilization for electric power production. I.V.Kurchatov and N.A.Dollezhal are appointed Scientific Project Leader and Chief Designer, respectively*

July 1, 1950 - *The Soviet Government issues a resolution establishing Institute 5 in Sukhumi (Sukhumi Institute of Physics and Engineering) under the direction of A.I.Koglashvili*

July 29, 1950 - *A Special Division is created within the PGU to guide activities in the field of peaceful atomic power applications headed by B.S.Pozdnyakov*

July 29, 1950 - *The Soviet Government issues a resolution establishing Ore Administration (Rudoupravlenie) 10 (now PO Almaz) in the city of Lermontov under the direction of I.M.Aleskeev*

October 24, 1950 - *The Soviet Government issues a resolution on constructing in the city of Frunze of Kyrgyz Ore Mining Complex 11 (now PO Southern Polymetal Complex) under the direction of N.V.Volokhov*

1950 - *I.E.Tamm, A.D.Sakharov and O.A.Lavrentiev propose using magnetic fields for thermal insulation of hot plasma from thermonuclear reactor walls*

1950 - *First ballistic missile, R-1 (SS-1a Scunner) is entered in the stockpile. The second ballistic missile, R-2 (SS-2 Sibling) is tested*

February 3, 1951 - *The Third Main Directorate of the SM SSSR headed by V.M.Ryabikov is established in order to facilitate scientific and technical progress in the area of missile and nuclear weapons carrier development*

1951 - *AI pilot reactor is commissioned at Complex 817 to produce tritium*

April 17, 1951 - *The Soviet Government issues a resolution establishing within the VGU of a Special State Design Institute (GSPI-14) headed by B.I.Nifontov to design ore mining and metallurgical enterprises*

April 17, 1951 - *NII 10 (now NII of Chemical Engineering, Moscow) is established based on the Giredmet to explore radioactive ore deposits and develop enrichment and hydrometallurgical processing flows*

May 5, 1951 - *The Soviet Government issues a resolution on self-sustained thermonuclear reaction feasibility studies*

July 24, 1951 - *The Soviet Government issues a resolution establishing Complex 9 (Eastern Ore Enrichment Complex, Zheltye Wody) directed by M.N.Bondarenko based on Ukrainian mines*

1951 - *The first industrial heavy-water reactor is put into operation. Scientific Leader is A.I.Alikhanov*

1951 - *Laboratory V, Obninsk starts the development of a nuclear reactor for the first Soviet atomic submarine. Project Manager is D.I.Blokhintsev*

November 18, 1951 - *First nuclear tests take place, during which the RDS-3 nuclear bomb is dropped from a carrier*

January 24, 1952 - *The Soviet Government issues a resolution establishing Factory 933 (now PO Instrument-Making Factory, Zlatoust-36, now Trekhgorny) under the direction of K.A.Volodin to produce nuclear weapons*

February 1952 - *Laboratory V starts the development of a shipboard reactor with liquid metal (lead-bismuth) coolant*

April 19, 1952 - *The Soviet Government issues a resolution on creating Central Design Bureau 1 (NII of Instrument Making) directed by S.V.Mamikonyan for dose monitoring equipment development*

June 12, 1952 - *PGU leaders initiate development of an atomic submarine equipped with T-15 torpedoes using thermonuclear warheads*

October 3, 1952 - *Great Britain starts its nuclear tests*

October 31, 1952 - *The United States tests a high-power liquid-deuterium thermonuclear device*

November 25, 1952 - *The Soviet Government issues a resolution on drafting a work plan of the atomic submarine project (Project 627) with A.P.Aleksandrov as Scientific Leader, V.N.Peregudov as Chief Designer of the submarine and N.A.Dollezhal as Chief Designer of the nuclear reactor*

March 16, 1953 - *The Soviet Government issues a resolution on joining up the PGU and the VGU to form the First Main Directorate headed by A.P.Zavenyagin*

June 26, 1953 - *The Presidium of the Central Committee of the CPSU issues a resolution on eliminating the Special Committee because of arrest of L.P.Beria. The Ministry of Medium Machine Building of the USSR (MSM SSSR) headed by V.A.Malyshev is established*

July 1, 1953 - *The Soviet Government resolves to incorporate the First and the Third Main Directorates headed by A.P.Zavenyagin and V.M.Ryabikov into the Ministry of Medium Machine Building of the USSR*

August 12, 1953 - *RDS-6s, the first Soviet thermonuclear single-stage bomb is tested*

November 4, 1953 - *The Government issues a resolution on incorporating the Ust'kamenogorsk Chemical and Metallurgical Works into the MSM SSSR to produce nonferrous metals for the nuclear industry*

November 20, 1953 - *The Government issues a resolution on designing and constructing the first atomic icebreaker. I.V.Kurchatov and A.P.Aleksandrov are appointed Scientific Leaders*

February 28, 1954 - *The United States for the first time tests a high-yield two-stage thermonuclear device*

March 10, 1954 - *Construction of Factory 820 (now the Angarsk Electrolysis Chemical Complex, Angarsk) for natural uranium processing is commenced*

April 10, 1954 - *The Government issues a resolution on developing the R-5N (SS-3 Shyster) intermediate-range ballistic missile with nuclear munitions*

May 5, 1954 - *Branch 1 of KB-11 headed by N.L.Dukhov is established in Moscow based on OKB-25 (now VNIIA) to develop nuclear munitions*

May 20, 1954 - *The Government issues a resolution on developing R-7 (SS-6 Sapwood), the first intercontinental ballistic missile*

June 27, 1954 - *The first world's nuclear power station is put into operation in Obninsk*

July 20, 1954 - *The Government of the USSR issues a resolution on constructing Instrument Factory 1134 (Penza Instrument Making Factory, now PO Start, Penza-19, now Zarechny) under the direction of Yu.P.Lyubovin to produce nuclear weapons parts*

July 20, 1954 - *The Government issues a resolution on building Factory 1135 (Novosibirsk Factory Khimapparat, now PO Sever, Novosibirsk) under the direction of B.A.Panov to produce nuclear weapons parts*

July 31, 1954 - *The Government of the USSR issues a resolution establishing NII-1011, the second Soviet nuclear center (now RFNC-VNIITF, Chelyabinsk-70, now Snezhinsk). D.E.Vasiliev and K.I.Shchelkin are appointed Director and Scientific Leader, respectively*

July 31, 1954 - *The Government of the USSR resolves to create the Northern Test Site at the New Island (Novaya Zemlya) Archipelago. Project Manager is E.N.Barkovsky*

September 4, 1954 - *Military exercises involving a real nuclear bomb explosion are conducted in the city of Totsk, Orenburg region under the command of G.K.Zhukov*

October 14, 1954 - *The Government of the USSR issues a resolution establishing the Western Ore Mining and Processing Complex under the direction of A.E.Stepanets based on Complex 6*

1954 - *The Air Defense Forces of the USSR are created*

February 1955 - *A Scientific and Technical Board for missile defense is established within the MSM SSSR*

February 1955 - *Air tests of the R-11FM, the first submarine ballistic missile take place at the Kapustin Yar missile testing ground*

February 25, 1955 - *A.P.Zavenyagin is appointed Minister of Medium Machine Building*

March 8, 1955 - *A nuclear reactor for the first atomic submarine is commissioned at Laboratory V*

March 14, 1955 - *The Government of the USSR issues a resolution on transferring the Directorate for Industrial Construction (Glavpromstroi) headed by A.N.Komarovsky from the Ministry of Internal Affairs to the MSM SSSR*

April 4, 1955 - *The Soviet Government issues a resolution on transferring the Eighth Directorate that ensured operation of joint uranium mining and processing enterprises abroad to the MSM SSSR*

April 14, 1955 - *Institutions involved in rocket building are separated from the MSM. A Special Arms Committee is established on their basis*

May 4, 1955 - *The Government issues a resolution on constructing Northern Kazakhh Complex 4 in Stepnogorsk under the direction of S.A.Smirnov to mine uranium and other materials for the nuclear industry*

May 1955 - *The Soviet Union approaches all nuclear states with a proposal to commit to stopping nuclear tests*

August 13, 1955 - *The Government issues a resolution on building the R-12 (SS-4 Sandal) intermediate range ballistic missile*

August 8 through 20, 1955 - *The first international conference on peaceful uses of nuclear energy involving Soviet specialists convenes in Geneva*

August 25, 1955 - *The Government issues a resolution on building R-13 (SS-N-4), a new submarine ballistic missile*

November 14, 1955 - *The Soviet Government issues a resolution on constructing Factory 825 for uranium isotope separation (Krasnoyarsk-45, now Zelenogorsk)*

November 22, 1955 - *The USSR conducts the first tests of the RDS-37, a new high-power two-stage thermonuclear device*

December 1955 - *The first fast neutron experimental reactor is put into operation at Laboratory V. A.I.Leipunsky is appointed Scientific Leader*

1955 - *The U-95A intercontinental heavy bomber is entered in the stockpile*

February 2, 1956 - *Nuclear tests involving the R-5 ballistic missile are conducted*

March 17, 1956 - *Rudoupravlenie 16 for uranium production under the direction of S.F.Zhiryakov (Zabaikalsk Ore Mining and Processing Complex) is incorporated into the MSM SSSR*

March 26, 1956 - *An agreement is signed establishing the Joint Institute for Nuclear Research, an international scientific organization in Dubna under the direction of D.I.Blokhintsev*

October 1956 - *New York International Conference adopts the IAEA Charter*

November 1956 - *A plan of construction in the USSR of a number of nuclear power stations in 1956 through 1960 is adopted*

December 17, 1956 - *The Government issues a resolution on building the R-16 (SS-7 Saddler) intercontinental ballistic missile*

1956 - *The USSR proposes that stationing of nuclear weapons in the Central Europe be banned*

1956 - *R-5 (SS-3 Shyster), the first Soviet intermediate range ballistic missile is deployed*

May 25, 1957 – *The Avangard Electromechanical Plant is established based on Factory 551 of KB-11 under the direction of M.A.Grigoriev*

April 30, 1957 - *M.G.Pervukhin is appointed Minister of Medium Machine Building of the USSR*

July 24, 1957 - *E.P.Slavsky is appointed Minister of Medium Machine Building of the USSR*

August 9, 1957 - *The first atomic submarine of Project-627 is launched*

August 1957 - *The USSR successfully tests the R-7 (SS-6 Sapwood), the first intercontinental ballistic missile*

1957 - *The R-12 (SS-4 Sandal) Soviet intermediate-range ballistic missile is tested*

September 29, 1957 - *A radio-ecological accident occurs at Complex 817*

October 10, 1957 - *Nuclear tests of the T-5 submarine combat torpedo are conducted at the Northern Test Site*

December 5, 1957 - *LENIN, the first atomic icebreaker is launched*

February 20, 1958 - *The Government issues a resolution on constructing in Navoi, Uzbek SSR of Uranium Mining Complex 2 under the direction of Z.P.Zarapetyan*

March 20, 1958 - *The Government issues a resolution on building D4, a new submarine ballistic complex with the R-21 (SS-N-5 Sark) missile*

March 31, 1958 - *The USSR announces a unilateral moratorium on nuclear testing*

April 28, 1958 - *Great Britain conducts the first tests of a high-yield thermonuclear device*

May 5, 1958 - *The Scientific and Technical Board of the MSM SSSR resolves to start commercial utilization of centrifuge isotope separation*

June 2, 1958 - *The Government issues a resolution on building the R-14 (SS-5 Skean) intercontinental ballistic missile*

October 24, 1958 - *The Soviet Government issues a resolution on transferring to the MSM SSSR of Factory 752 (the Kirovo-Chepetsk Chemical Plant) under the direction of Ya.F.Tereshchenko producing fluorine compounds*

October 31 through November 4, 1958 - *Trilateral moratorium of the USSR, the United States and Great Britain on nuclear tests is commenced*

October 31, 1958 - *Trilateral negotiations are initiated in Geneva on ceasing nuclear tests*

December 17, 1958 - *The first Soviet atomic submarine is put into operation*

May 13, 1959 - *The Government issues a resolution on building the R-9a (SS-8 Sasin) intercontinental ballistic missile*

July 21, 1959 - *Laboratory V accomplishes construction of the BR-5 fast neutron reactor using plutonium dioxide as the nuclear fuel*

September 18, 1959 - *The Soviet Union approaches the Fourteenth Session of the UN General Assembly with a program for general and complete disarmament*

September 1959 - *The Soviet Union, the United States, Great Britain and France agree on establishing a Disarmament Commission*

December 1, 1959 - *The Treaty declaring Antarctic the first officially recognized nuclear-free area is open to signing*

Late 1959 - *The Strategic Rocket Forces of the USSR are created*

December 31, 1959 - *The Government issues a resolution on putting the LENIN atomic icebreaker into pilot operation*

January 14, 1960 - *N.S.Khrushchev enunciates a new military doctrine of the USSR resting upon ballistic nuclear-warhead missiles as a decisive security safeguard*

February 11, 1960 - *The United States proposes signing a treaty banning nuclear tests in the atmosphere, in space and under water and restricting the yield of underground nuclear explosions*

February 13, 1960 - *France starts its nuclear tests*

March 1960 - *The Geneva Disarmament Commission takes up its duties*

Chapter 1

First Steps of the Soviet Atomic Project. Role of Intelligence

Contents

Introduction

The development of the first Soviet atomic bomb was a heroic labor deed of the Soviet nation that managed to create a new atomic industry, a nuclear weapons center and a testing ground under the post-war devastation conditions. A great multidisciplinary scientific team was created, whose goal was to provide a material, scientific and technical basis for the atomic industry and develop Soviet atomic weapons.

A remarkable contribution to laying the scientific foundation for the Soviet nuclear weapons development was made by the Soviet intelligence, which managed to acquire and pass along diversified valuable data including both the concept, and specific scientific and technical data on the atomic project.

Today there are a lot of different publications highlighting different aspects of the Soviet atomic project's history. They contain diverse data on how the program of the first Soviet atomic bomb development has been implemented, and present different opinions on its individual phases.

This Chapter contains the key factual information on the Soviet atomic project implementation background. As for significance evaluation of the data supplied by the Soviet intelligence, we mainly rested upon the contents of the book *Soviet Atomic Project. Volume 1. 1938-1945. Part 1* edited by L.D.Ryabev, Nauka, Moscow, 1998.

The bulk of intelligence is divided into five sections, namely "Atomic Bomb Design", "Basic Physical Data", "Isotope Separation", "Nuclear Reactors" and "Work Arrangement".

We withhold detailed comments on the particular role of these data, since this information has not been unclassified in its complete scope; however, the list of these data speaks for itself. It is noteworthy that intelligence included both description of both basic ideas underlying the development of an atomic bomb and atomic productions and their feasibility, and specific diversified physical and engineering data that have directly affected on the concepts of our experts.

The following statement is likely to be close to the truth: During the period from 1941 through 1945 of paramount significance for the Soviet atomic project development was the intelligence, whereas in 1946 through 1946 prevailed our own efforts and accomplishments. 1945 is the boundary year, which is accredited to the victory of the Soviet Union the Great Patriotic War and the possibility to focus national efforts on practical dealing with the atomic problem. Along with this, it is necessary to emphasize the outstanding role of our specialists during the first phase, and that of I.V.Kurchatov in the first line, in intelligence analysis, comparison with our data, verification and evaluation, as well as in specifying the basic conceptual lines of our atomic project. As early as at this stage there was created a core of the expert team that at the second three-and-a-half-years' stage met the atomic challenge. Without stage one (if we had to start from nothing after the Hiroshima and Nagasaki explosions in 1946) the process of the Soviet atomic bomb development would have slowed down substantially. On the other hand, should the basic national decisions on speeding up the atomic project have been made before August 1945, this would have hardly shortened the time frame of building the atomic bomb. The fact is that the Soviet Union had no source material (natural uranium) at that time and could not get it from Germany or Czechoslovakia (where it was later actually obtained from) in the war environment. It seems hardly possible that uranium production at domestic enterprises could be developed under the wartime conditions. Consequently, one should recognize that the atomic bomb was built not later than it could be built.

The Soviet atomic project yielded in 1949 a prototype of the first atomic bomb and its successful tests on August 29, 1949. The lag between the Soviet Union and the United States as to the nuclear weapons development made about four years. The United States by that time had performed 8 nuclear tests listed in Table 1.1.

Table 1.1

U.S. Nuclear Tests from 1945 through 1948

	Date	Location	Type	Height, m	Yield
1	**Jul 16, 1945**	**Alamogordo, United States**	**surface; tower**	**30.5**	**23 kt**
2	**Aug 06, 1945**	**Hiroshima, Japan**	**atmospheric; air bomb**	**580**	**15 kt**
3	**Aug 09, 1945**	**Nagasaki, Japan**	**atmospheric; air bomb**	**503**	**21 kt**
4	**Jun 30, 1946**	**Bikini**	**atmospheric; air bomb**	**159**	**23 kt**
5	**Jul 24, 1946**	**Bikini**	**underwater;**	**-27.5**	**23 kt**
6	**Apr 14, 1948**	**Enewetak**	**surface; tower**	**61**	**37 kt**
7	**Apr 30, 1948**	**Enewetak**	**surface; tower**	**61**	**49 kt**
8	**May 14, 1948**	**Enewetak**	**surface; tower**	**61**	**18 kt**

Nuclear explosions 1 and 3 were produced by an implosion-type plutonium bomb, which became a prototype for the Soviet atomic bomb. Nuclear explosion 2 was produced by a gun-type uranium atomic bomb. Its analogue was under development but was not built at the first stage of the Soviet atomic program. Tests 4 and 5 were the first military exercises, called Operation Crossword, involving a nuclear explosion, in which participated about 42,000 people. The nuclear device used was the same as during tests 1 and 3.

The year 1948 saw the tests of next-generation implosion-based atomic bombs using advanced physical schemes.

In 1949, the United States suspended their nuclear tests till early 1951.

It is interesting to study the data on the U.S. nuclear production and stockpile of that time to evaluate the strategic situation that had formed by 1949.

In 1949, the United States had four operating industrial nuclear reactors to produce weapon-grade plutonium, two of which had been commissioned in 1944 and one in early 1945. By the end of the year 1949 these reactors had produced about 700 kg of weapon-grade plutonium, including about 120 kg by the end of 1945. Let us note that in late 1949 the USSS hardly possessed more than 10 kg of plutonium.

Table 1.2 shows the amount of natural uranium contained in mined and produced ores (concentrate) in the United States and in Russia up to 1949.

Table 1.2

Production of natural uranium (in tons of uranium)

Year	before 1945	1945	1946	1947	1948	1949	Total
U.S.	3140	320	2680	1080	1310	1470	10000
USSR	0	115	110	340	635	1270	2470

By 1949, the stock of mined natural uranium available in the Soviet Union was about 25% of that of the United States. At that, 73% of natural uranium were delivered from abroad, mostly from Germany and Czechoslovakia. The capacities of the uranium-mining industry were gradually enhanced to catch up with those of the U.S., and the inflow of natural uranium in the USSR in 1949 was as high as 86% of that in the United States.

Table 3 shows the amount of nuclear devices produced by the U.S. atomic industry of those years, as well as their total megatons.

Thus, as of 1949, the United States possessed a considerable nuclear arsenal including 170 nuclear devices with the total energy yield of 4.2 Mt; the average yield was about 25 kt.

Table 1.3

U.S. nuclear stockpile in 1945-1949

Year	Total number of nuclear weapons	Total megatons
1945	2	0.04 Mt
1946	9	0.18 Mt
1947	13	0.26 Mt
1948	50	1.25 Mt
1949	170	4.19 Mt

Essentially, the entire U.S. stockpile of 1949 was based on the implosion-type plutonium physical scheme.

The U.S. atomic industry was constantly enhancing its capacities in the development of nuclear devices, and the stockpile produced by 1949 was rather impressive. Strategic aircraft was intended to deliver it to the Soviet territory, and in order to enhance its military capabilities there were actively deployed military outposts along the Soviet boards in the territories of U.S. allies.

These facts highlight the vital necessity of the efforts implemented by the USSR to end the U.S. atomic monopoly, which was broken on August 29, 1949. There lied a lot of effort ahead, the results of which were decisive in whether or not the Soviet Union could end the enormous nuclear superiority of the United States.

1. Milestones of the Soviet Atomic Project

1.1. First Steps Towards Nuclear Infrastructure Development

Even though the pre-history of the Soviet project on nuclear power utilization dates back to the pre-war years, we will start our analysis from 1942, when conceptual decisions to commence the Soviet atomic project were made at the supreme state level. The first of these decisions was a resolution of September 28, 1942 issued by the State Defense Committee to arrange uranium-related activities. In compliance with this resolution, the Soviet Academy of Sciences was to resume nuclear fission energy feasibility studies, and before April 1, 1943 prepare a report of the feasibility of building an atomic bomb or using uranium fuel for a nuclear reactor.

For the first time, for these purposes it was intended to create a nuclear infrastructure, the core of which was composed of four institutions:

- Special Laboratory of the Soviet Academy of Sciences established in compliance with this resolution, which was to coordinate the entire atomic project;
- Radium Institute in charge of uranium isotope separation by thermal diffusion that had gained a certain practical experience in this area by that time;
- Institute of Physics and Mathematics of the Soviet Academy of Sciences to study the centrifuge uranium isotope separation matters, in which at that time this direction was developed by F.F.Lange;
- Leningrad Institute of Physics and Engineering, which was to produce the required amount of U-235 for initial investigations.

A.F.Ioffe, Member of Academy was made responsible for the implementation of this program in the Soviet Academy of Sciences.

The first separation facilities were to be constructed by March 1943 to produce some uranium enriched in U-235 isotope.

In order to support these activities, a number of ministries and agencies were to provide the Academy of Sciences with specific materials and equipment. They were:

- The People’s Commissariat of Heavy Machine Building;
- The People’s Commissariat of Finances;
- The People’s Commissariat of Ferrous Metallurgy;
- The People’s Commissariat of Nonferrous Metallurgy;
- The People’s Commissariat of Foreign Trade;
- The Chief Civil Air Fleet Directorate;
- The Council of People’s Commissars (Sovnarkom) of the Tatar ASSR.

At the same time, the absence of required stocks of mined uranium was recognized one of the basic factors to hinder the program implementation. In this connection, on November 27, 1942, the State Defense Committee issued a resolution on uranium production. This resolution charged the People’s Commissariat of Nonferrous Metallurgy with arranging uranium ore production and processing at the Taboshar deposit with the planned annual capacity of 4 tons of uranium salts. As for the Radium Institute, it was to develop a production flow for making uranium concentrate from uranium salts produced from Taboshar ores. The resolution also charged the Committee for Geology with exploring new uranium ore deposits.

These two resolutions were the first examples of the comprehensive approach to implementing the Soviet atomic project, which implied laying the foundation of the Soviet nuclear infrastructure. These resolution were not implemented in their entire scope and the work was not completed on schedule, but this not in the least belittles their fundamental importance.

1.2. Some Results of the Soviet Atomic Project Realization as of 1942

1.2.1. One of the leading institutions in the atomic project prior to the creation of the Special Laboratory of the Soviet Academy of Sciences was the Radium Institute. Some of its basic efforts included

- investigations into thermal diffusion in liquid media as applied to the problem of isotope separation of uranium and other heavy elements;
- investigations into gas-phase thermal diffusion as applied to light elements;
- estimation of critical masses of U-235 for the case of both fast and slow neutrons. The estimated critical mass of U-235 for fast neutrons was about 8 kg;
- evaluation of effects of neutron reflectors surrounding U-235 on the critical mass value. According to the estimates, application of neutron reflectors could help reduce the critical mass of U-235 to a half;
- estimation of the critical mass of Pa-231 (Pa-231 is a long-lived radionuclide with the half-life $\grave{O}_{1/2}$ of $3.28 \cdot 10^4$ years and is a member of the radioactive-decay series of U-235. The equilibrium content of Pa-231 in the uranium concentrate as against U-238 is $3.3 \cdot 10^{-5}$%. In 1942 the character of nuclear fission of Pa-231 and U-235 was considered alike, and their critical masses were, therefore, estimated as identical. Along with this, the amount of Pa-231 occurring in nature was realized to be too small for reckoning on it as a material for an atomic bomb. Actually, as to the fission process, Pa-231 is a threshold isotope, and like U-238 it does not have critical mass.

1.2.2. One of the highlights in the history of the Soviet atomic project in 1942 were the proposals of G.N.Flerov set forth in his letter to I.V.Kurchatov in March - June 1942. These proposals contained a conclusion that it was feasible to produce a chain reaction involving fast neutrons with U-235 and Pa-231. The probable number of secondary neutrons ν produced at nuclear fission driven by fast neutrons was estimated from 2 to 3 neutrons; the probable effective nuclear fission cross-section of these isotopes s_f for fast neutrons was estimated at approximately 3 barns. The estimated probable critical mass of U-235 and Pa-231 ranged between 0.5 and 10 kg.

In his proposals, G.N.Flerov noted that explosive nuclear fission was considerably hindered by the natural neutron background comprising three components:

- cosmic-ray neutrons;
- spontaneous-fission neutrons;
- neutrons produced by nuclear α-decay in the (α,n) reaction.

G.N.Flerov was the first to point out how important in terms of the amount of energy released by a nuclear explosion was the influence of the system's supercriticality at the detonation moment and disruption time of fissile material during the explosion. His letter gives approximate values of the energy released by a nuclear explosion.

The letter contained a general layout combining the gun-type and the implosion-based systems. In order to transfer the system from the subcritical to the supercritical state, this device was to use the energy of HE explosion.

1.2.3. The information that I.V.Kurchatov has first familiarized himself with the intelligence reports received from Great Britain refers to the fall of 1942. On November 27, 1942 he submitted a report to V.M.Molotov, in which he analyzed the intelligence and formulated a number of proposals as to the arrangement of activities aimed at the Soviet nuclear weapons development. Of real interest are the results of this analysis and the proposals.

I.V.Kurchatov highlighted the accomplishments of Great Britain in establishing the feasibility of a nuclear reactor based on natural uranium and heavy water. A unique experiment that made this conclusion possible was performed due to the availability of about 180 kilograms of heavy water brought from Norway and being almost the world's total stock of this material.

One of the key physical indices that determines the possibility of a chain reaction in an atomic bomb is the effective cross-section of U-235 fission driven by fast neutrons. As the measurements performed in Great Britain showed, s_f was 2.1 barns for the neutron energy E_n of 0.35 MeV and 1.5 barn for 0.8 MeV. (The average cross-section value in this neutron energy range as identified at that time was 1.8 barn, whereas today's value is 1.25 barn). Based on these data, scientists of Great Britain estimated the critical mass at 9 to 43 kilograms. As noted by I.V.Kurchatov, in Great Britain there were considered the methods of uranium isotope separation by means of thermal diffusion, a centrifuge and gaseous diffusion. This consideration lead to the conclusion that compared with the centrifuge and thermal-diffusion separation, the gaseous-diffusion method was the most promising one as applied to uranium isotope separation.

Having analyzed the documents, I.V.Kurchatov drew a number of conclusions:

- as to the atomic project, the Soviet Union lagged behind Great Britain and the United States;

- based on the materials one could not conclude that uranium bomb was feasible; nevertheless, the data undoubtedly implied that Great Britain and the United States had already arrived at this conclusion;
- in order to speed up the work in the Soviet Union, it was necessary to involve in the atomic project a number of specialists (listed: A.I.Alikhanov, Yu.B.Khariton, Ya.B.Zeldovich, I.K.Kikoin, A.P.Aleksandrov, A.I.Shalnikov);
- it was necessary to establish a Special Committee of the State Defense Committee to manage the atomic project (this proposal was materialized as late as in August 1945) that could include such scientists as A.F.Ioffe, P.L.Kapitza, N.N.Semenov.

I.V.Kurchatov proposed that access to the intelligence be strictly limited, so that these data could be available to two or three scientists. Along with this, in part this information should be available for a wider range of specialists. For example, he suggested that Ya.B.Zeldovich and Yu.B.Khariton, who worked at that time at the Institute of Chemical Physics, be familiarized with the intelligence on the uranium isotope separation technology so that they could evaluate the prospects of the gaseous-diffusion method, as well as the capabilities of the centrifuge technology proposed by F.F.Lange.

I.V.Kurchatov formulated a number of issues worth clarifying using the intelligence means:

- specific features of the technology used in Great Britain to identify uranium cross-sections for both fast and slow neutrons (including those for the system based on uranium and heavy water);
- number of secondary neutrons at U-235 nuclear fission driven by fast neutrons;
- data on the creation and operational features of a facility model for gaseous-diffusion uranium isotope separation;
- information on the efficient way to produce uranium hexafluoride.

1.2.4. In late 1942 – early 1943 the leading specialists involved in the uranium project drew up a number of proposals necessary to implement the resolution of the State Defense Committee on arranging uranium activities.

I.V.Kurchatov in his proposals addressed to A.F.Ioffe (responsible for the implementation of the State Defense Committee’s resolution) also pointed out that by December 1942

- the Radium Institute had made preliminary arrangements for the work in a number of areas, namely:

  - ✓ production of a considerable amount (about one kilogram) of uranium hexafluoride;
  - ✓ development of equipment for physical studies;
  - ✓ building a lab facility for thermal-diffusion uranium isotope separation in the gas phase based on uranium hexafluoride (in two months the facility was to produce 5 g of uranium with the enrichment in U-235 up to 4%);
  - ✓ investigations into physical and chemical properties of uranium hexafluoride (equation of state, corrosive action on structural materials, viscosity, thermal conductivity);
  - ✓ experimental studies of thermal diffusion in liquid medium.
- the Physical Institute of Soviet Academy of Sciences possessed a cyclotron chamber enabling production of ~1-MeV deuterons.
- in order to carry out the work, the amount of radium available at the Radium Institute was sufficient, and, in addition, it was necessary to get from abroad 1-2 mg of protactinium.

In December 1942, A.I.Alikhanov submitted to A.F.Ioffe his proposals. He suggested

- that in order to ensure the secrecy, along with secret activities, there should be carried out non-secret activities related to adjacent subjects and methods that were to be considered follow-ups to the pre-war projects;
- that 1 to 1.5 g of radium should be provided to produce varied-intensity neutron sources (based on the mixture of radium and beryllium) (this amount of radium when used in a radium-beryllium neutron source enabled production of a source with the neutron yield of 10^6 neutrons per second);
- that in order to provide the Special Laboratory with equipment, there should be delivered the scientific equipment available in Yerevan and Leningrad;
- that considerable amount of uranium should be purchased;
- that employees of the laboratories under the direction of A.I.Alikhanov and I.V.Kurchatov should be engaged to work in the Special Laboratory. Should the project require cyclotron transportation and operation, a number of specialists of the Radium Institute and Leningrad Institute of Physics and Engineering were to be involved in the activities.

In January 1943, V.G.Khlopin submitted to A.F.Ioffe his proposal regarding the way of atomic project arrangement. According to V.G.Khlopin, the most essential issues to be addressed were

- whether it was possible to produce a chain reaction of U-235 nuclear fission driven by fast or slow neutrons using natural uranium or it was necessary to beforehand separate it;
- what the critical mass of material was for different types of chain reaction;
- whether or not it was feasible to separate U-235 isotope in the amount necessary for practical application, and what method was the most promising one. Again, V.G.Khlopin pointed out fundamental significance of producing a chain reaction using natural uranium, if there were any capabilities for that.

As can be judged from V.G.Khlopin's list of questions, he had not been acquainted with the intelligence to I.V.Kurchatov. The top-priority directions of the Special Laboratory's efforts, according to V.G.Khlopin, include:

- experimental verification and identification of parameters of the centrifuge method proposed by F.F.Lange for uranium isotope separation;
- production of a required stock of pure U-235 isotope using the facility devised by F.F.Lange and identify the main parameters of fission process;
- experimental verification of the feasibility of uranium isotope separation by thermal diffusion in gases and liquids;
- evaluation and verification of the capabilities of the diffusion uranium isotope separation method;
- production of required stocks of UF_6 and UCl_5 (1 to 2 kilograms) to carry out isotope separation studies;
- production of required stocks of highly pure uranium metal (about 3 kilograms);
- experimental feasibility study of a chain reaction with natural uranium.

2. Atomic Project in 1943

2.1. First Efforts of the Special Laboratory for Atomic Nucleus

The basic work under the Soviet atomic project in 1943 was connected with establishment and development of the Special Laboratory for Atomic Nucleus of the Soviet Academy of Sciences established in compliance with the State Defense Committee's resolution.

In January 1943, S.V.Kaftanov, State Defense Committee representative and A.F.Ioffe, responsible for project implementation as set forth in the State Defense Committee's resolution specified the basic organizational structure of the forthcoming project. Centrifuge uranium isotope separation and studies of U-235 properties were mainly the responsibility of specialists of the Leningrad Institute of Physics and Engineering and a number of physicists representing other institutes of the Soviet and Ukrainian Academies of Sciences and were to be directed by A.I.Alikhanov. Development of technologies for uranium separation from uranium ores and uranium isotope separation by thermal diffusion was entrusted to the Radium Institute headed by V.G.Khlopin. Research on the first group of tasks was to be carried out mostly in Moscow and research on the second group of tasks in Kazan'. Professor I.V.Kurchatov was to manage the overall project. At that, it was planned to provide access to the problem in general merely to S.V.Kaftanov, A.F.Ioffe, A.I.Alikhanov, I.V.Kurchatov and I.K.Kikoin. Taking into account the information received from Great Britain, S.V.Kaftanov and A.F.Ioffe suggested that along with the centrifuge and the thermal-diffusion isotope separation methods that were under development in the USSR there should be developed the method of gaseous diffusion through porous barriers. These proposals were addressed to V.M.Molotov, Deputy Chairman of the GKO.

The resolution of the State Defense Committee of February 11, 1943 revised the arrangement of the uranium project. This resolution charged M.G.Pervukhin and S.V.Kaftanov with immediate supervision of the atomic project, including systematic support of the activities of the Special Laboratory for Atomic Nucleus. I.V.Kurchatov was made scientific leader of the project. By July 1943 I.V.Kurchatov was to carry out necessary investigations and report on the feasibility of an atomic bomb or production of uranium fuel for nuclear reactors.

The initial draft of the resolution entrusted general supervision over the atomic project to M.G.Pervukhin, S.V.Kaftanov and A.F.Ioffe. The principal report to the State Defense Committee on the atomic problem in July 1943 was also to be drawn up by A.F.Ioffe and I.V.Kurchatov. That A.F.Ioffe who had been responsible for the problem according to the previous resolution was not included in the final revision of the State Defense Committee's resolution can probably be attributed to the unsatisfactory rate of the progress.

In February 1943, A.F.Ioffe advanced two initiatives within the atomic program. The first one was to arrange a delivery from the United States of ~ 1 mg of protactinium. The requirement to have this material was explained by the necessity to carry out research into spontaneous fission of this isotope. The second initiative by A.F.Ioffe was the proposal he addressed to Director of the Institute of Organic

Chemistry of the Soviet Academy of Sciences A.N.Nesmeyanov on arranging studies of organometallic compounds of uranium. The purpose of this initiative was to find materials suitable for uranium isotope separation using the gaseous-diffusion method.

In late January 1943, I.V.Kurchatov and A.I.Alikhanov drew up a work plan of the Special Laboratory for Atomic Nucleus for the year 1943, which was submitted to S.V.Kaftanov and forwarded to V.M.Molotov along with the draft of the above State Defense Committee's resolution. This plan provided for carrying out work in three subject areas:

- uranium fission physics;
- isotope separation;
- chemical research.

The first subject area was to comprise the following basic lines:

- well-founded demonstration of unfeasibility of a natural uranium-based atomic bomb (this task was called forth by obtaining from abroad of a required amount of uranium metal);
- well-founded demonstration of unfeasibility of a reactor based on natural uranium and ordinary water (this task was called forth by the delivery to the Special Laboratory of 100 kilograms of uranium salts);
- identification of the effective cross-section of U-235 fission by fast neutrons with the energy ranging from 0.2 to 0.8 MeV;
- development of a cyclotron to produce varied-energy high-power neutron flows;
- development of diagnostic methods to study the initial phase of a chain reaction implemented with natural uranium and uranium partly enriched in the U-235 isotope.

The second subject area included the following basic directions:

- development of the centrifuge uranium isotope separation method by F.F.Lange (examination of the method was entrusted to I.K.Kikoin);
- production by the Radium Institute of uranium partly enriched in the U-235 isotope (about 4%) by thermal diffusion;
- development of the gaseous-diffusion method for uranium isotope separation (this direction was guided by I.V.Kurchatov, I.K.Kikoin and A.I.Alikhanov);
- feasibility study of uranium isotope separation by the electromagnetic method (headed by L.A.Artsimovich).

The third subject area encompassed the following basic lines:

- production by the Radium Institute of 1 kilogram of uranium hexafluoride and its characterization;
- production by the Radium Institute of 10 kilograms of uranium metal.

2.2. Organizational Practices to Arrange and Consolidate the Efforts of the Special Laboratory for Atomic Nucleus

Appointment of I.V.Kurchatov head of the Special Laboratory for Atomic Nucleus (Laboratory 2 of the Soviet Academy of Sciences) was an important step towards strengthening the organizational structure of the atomic project. This appointment was executed on March 10, 1943 by resolution 122 extending over the Soviet Academy of Sciences.

In order to provide the atomic project managers, who were to cooperate with scholars in the Soviet Academy of Sciences, with a corresponding status, in 1943 it was decided to promote I.V.Kurchatov and A.I.Alikhanov full members of the Soviet Academy of Sciences. On September 27-29 I.V.Kurchatov and A.I.Alikhanov were elected full members of the Soviet Academy of Sciences at a general meeting of the Academy’s Department of Physics and Mathematics (Secretary Member of Academy of this department was A.F.Ioffe). On September 29, 1943, the general meeting of the Soviet Academy of Sciences validated the elections conducted by the Department of Physics and Mathematics, which made A.P.Aleksandrov and I.K.Kikoin, principal assistants of I.V.Kurchatov at implementing the first stages of the atomic project, corresponding members of the Academy.

In March 1943, I.V.Kurchatov proposed involving into the atomic project of L.D.Landau and P.L.Kapitza. He noted that unique conditions of nuclear explosion required top-level theoretical analysis of the processes, which necessitated involvement of professor L.D.Landau. Isotope separation and development of corresponding facilities required assistance of P.L.Kapitza, an outstanding scientist with a great deal of knowledge of physics and a talented engineer.

In May 1943, I.K.Kikoin evaluated the progress in the development of the centrifuge isotope separation facilities. In his report to I.V.Kurchatov he rated it as unsatisfactory, noting, among others, absolute absence of experiments with any facility design. He also pointed out serious design drawbacks of the facilities then under development.

In July 1943 in his report I.V.Kurchatov emphasized staff-related consolidation of Laboratory 2 during the first half of the year 1943. Laboratory projects involved both specialists who had been working on the uranium problem before the war (I.V.Kurchatov, Ya.B.Zeldovich, Yu.B.Khariton, G.N.Flerov, K.A.Petrzhak) and prominent experts who had been earlier dealing with other problems (A.I.Alikhanov, S.A.Khristianovich, I.K.Kikoin, M.O.Kornfeld, I.Ya.Pomeranchuk, B.V.Kurchatov). Research under atomic project involved expert teams in a number of scientific institutions, such as the Radium Institute headed by V.G.Khlopin, the Institute of Organic Chemistry headed by A.N.Nesmeyanov, Moscow State University headed by V.I.Spitsyn, the Institute of Rare Metals. All the outsourced teams worked according to special task orders issued by Laboratory 2.

In August 1943 M.O.Kornfeld submitted to I.V.Kurchatov a memorandum on the means of producing heavy water for research purposes of Laboratory 2. In the memorandum he noted that in order to produce heavy water with low enrichment in deuterium there might be used capacities of the Moscow Electrolysis Plant. Along with that, in order to produce heavy water with high deuterium content it was reasonable to utilize the capacities of the Chirchik Electrolysis Plant.

In compliance with the August 1943 resolution of the State Defense Committee, TsAGI was given a task to develop under the direction of S.A.Khristianovich a draft design of a gaseous-diffusion facility for uranium isotope separation. This resolution also instructed M.G.Pervukhin and S.V.Kaftanov to submit in December 1943 a proposal to the State Defense Committee for gaseous-diffusion facility construction.

In 1943 I.V.Kurchatov reported to M.G.Pervukhin on the progress in the atomic problem. In his report he pointed out that

- in September 1943 there had been started tests of a centrifuge for isotope separation. The tests had been performed with a mixture of light gases. There had been observed a separation effect; the designed parameters of the facility, however, had not been implemented. The uranium isotope separation experiments had been delayed for lack of uranium hexafluoride;
- uranium hexafluoride production required uranium metal that had been stockpiled by the Institute of Rare Metals. For the first time in the USSR there had been produced a small amount of uranium hexafluoride (NII-42, People’s Commissariat of Chemical Industry). The properties of uranium hexafluoride and its affects on various materials had not been studies yet and this effort was to be carried out by NII-42. Initially this task had been entrusted to the Radium Institute, which, however, failed to cope with it;
- the Radium Institute had measured the characteristics of U-235 fission driven by fast neutrons. These were the first Soviet Union’s experimental data in this area;
- heavy water production was necessary to create a nuclear reactor operating with natural uranium and heavy water. There had been developed a layout

of an experimental facility to produce heavy water. This layout had been forwarded to the People's Commissariat of Chemical Industry to build the facility;

- the TsAGI laboratory had failed to develop the layout of the gaseous-diffusion facility on schedule. Independently of this project Laboratory 2 was developing a simplified model of a gaseous-diffusion facility in Sverdlovsk;
- there was a delay with building the cyclotron since electromagnet delivery date had been postponed;
- experiments conducted by Laboratory 2 demonstrated inapplicability of standard products of Soviet graphite factories for uranium-graphite reactors, since standard uranium contained a lot of neutron-absorbing impurities. Therefore, it was necessary to address a new problem, namely production of pure graphite. As requested by Laboratory 2, this task had been assigned to the Moscow Electrode Plant.

In December 1943, M.G.Pervukhin ordered head of NII-42 G.I.Gavrilov to speed up uranium hexafluoride production. At that, since April 1944 there were to be produced 10 kilograms of UF_6 per month, and there was to be designed a factory with the daily output of 100 kg of uranium hexafluoride. In 1944, NII-42 was to study the physical and chemical properties of UF_6 and report the outcome of the investigations to Laboratory 2.

3. Basic Scientific and Technical Data Acquired by the Soviet Intelligence

The published unclassified files unveil a vast body of data acquired by the intelligence related to different aspects of atomic project implementation. Significance of these data under the conditions of wartime-associated lack of home investigations is obvious for specialists and was repeatedly emphasized by I.V.Kurchatov, scientific leader of our atomic project. We deem it worthy to divide these data into several basic areas in order to apprehend these consistently. The data on each area are listed in the chronological order as these were acquired.

In addition to this, some basic scientific and engineering facts are presented in the appendices as they are reported in the published intelligence files.

3.1. Atomic Bomb Design

1941 - 1942

1. According to the data obtained from Great Britain, a promising material for atomic bomb development was uranium-235, one of the isotopes of natural uranium characterized by efficient fissionability.

2. According to the data obtained from Great Britain, this material in the amount less than the critical mass was stable and safe, whereas, in a mass of the material greater than the critical mass there took place a chain reaction of nuclear fission leading to an enormously powerful explosion.

To achieve that, an atomic bomb was to consist of two similar subcritical halves, whose total mass, however, was greater than the critical value. In order to produce an explosion, those two parts were to be integrated (gun-type devices). The required mass approach velocity was estimated at 6,000 feet per second (1.8 km/sec). It was noted that at lower velocities the chain reaction ceased and explosion power reduced, the latter being, however, still much higher than that when a conventional explosive was used.

The energy release by a nuclear bomb explosion was noted to be equivalent to the effect of a blast produced by 1,600 tons of TNT.

1943

3. There were data received from Great Britain on the applicability for the atomic bomb development of element-94 with mass number 239 (plutonium-239), which could be produced in uranium piles.

4. With regard to the data from Great Britain on the process of spontaneous fission of uranium I.V.Kurchatov noted that it did not allow keeping uranium in a supercritical mass up to the moment of explosion.

5. Concerning the data from Great Britain on applying the gun principle to the atomic bomb development, I.V.Kurchatov pointed out this method to be not novel for them and a similar project to have been proposed by G.N.Flerov.

6. Regarding the data from Great Britain on the amount and spectrum of secondary neutrons and cross-section of fission of uranium-235, I.V.Kurchatov emphasized the importance of such characteristics for identifying the minimum bomb size (critical mass of uranium-235).

7. After analyzing the intelligence on the possibility of eka-osmium (plutonium) production in a uranium pile, I.V.Kurchatov advanced a thesis that that way could make it possible to get the necessary material for the atomic bomb.

1945

8. There were data obtained on the development in the United States of two techniques for atomic bomb explosion:

- ballistic (gun-assembly principle);
- internal explosion technique (implosion principle).

The designed energy release from an atomic bomb with a 3-t mass ranged from 2,000 to 10,000 tons of explosive. A nuclear explosion would entail not only a blast wave, but also high temperature and strong radioactive effects.

9. I.V.Kurchatov declared the implosion method to be of great interest, correct in principle and worthy of careful analysis.

10. Information was acquired that the U.S. atomic bomb was provided with a neutron reflector of beryllium oxide.

11. Data were obtained on a method to make implosion-type atomic bomb explosion symmetric by arranging detonators and using various-action high explosive layers.

12. Preliminary data were acquired on the U.S. implosion-type atomic bomb design.

13. Detailed data were obtained on the U.S. implosion-type atomic bomb design, including a description of

- a neutron initiator in the form of a polonium-beryllium neutron source;
- an active material in the form of plutonium δ-phase;
- a uranium metal shell;
- an aluminum shell;
- an explosive and a symmetrization lens system;
- atomic bomb assembly features.

3.2. Basic Physical Data

1941-1942

1. According to the data from Great Britain, the critical mass of uranium-235 ranged from 9 to 43 kg depending on the hypothesized fission cross-section of uranium, which required experimental verification.

Let us point out that the upper value of the above range (43 kg, which is close to the actual critical mass of uranium-235 making about 50 kg) specified in the initial data was not included in the report of the NKGB (People’s Commissariat of State Security) to L.P.Beria and, further, in the report of L.P.Beria to I.V.Stalin, which handled the value of 10 kg as the critical mass of uranium-235.

1943

2. The data from Great Britain were pointed out to confirm uranium's ability to demonstrate spontaneous fission (discovered by G.N.Flerov and K.A.Pertzhak).

3. The data from Great Britain contained actual nuclear fission cross-sections σ_f for U-235 at the level of $(2\text{-}3)\cdot 10^{-24}$ cm^2 within the neutron energy range from 200 to 800 keV. I.V.Kurchatov emphasized significance of those data, since earlier experimental data covered only a small neutron energy range, whereas theoretical data provided different results for a large neutron energy range from 1 to 1,000 keV.

In his analysis I.V.Kurchatov gave two theoretical curves for fission cross-sections, according to which within the neutron energy range from 10^2 to 10^6 eV the fission cross-section made $(1\text{-}3)\cdot 10^{-24}$ cm^2 and $(0.03\text{-}3)\cdot 10^{-24}$ cm^2, correspondingly. (Let us note that according to the present-day data, the fission cross-section σ_f of uranium-235 in the energy range from 200 to 800 keV is 1.32 barn.)

4. The data from Great Britain specified the number of secondary neutrons released per fission ($\nu = 2\text{-}3$ neutrons) and contained the energy spectrum of secondary neutrons.

I.V.Kurchatov pointed out the necessity to find out the type of neutrons (fast or slow), to which these data referred, and stressed their significance if these refer to fast neutrons (let us note that according to the present-day data, as applied to uranium-235, ν makes 2.42-3.04 within the entire energy range from thermal neutrons up to the energies of several MeV, and energy distribution of secondary neutrons is almost independent of the energy of neutrons that split nuclei).

5. As for the applicability of eka-osmium-239 (plutonium) for the atomic bomb, I.V.Kurchatov emphasized the necessity to obtain data on the features of nuclear fission of this isotope.

1944

6. There was information received on the phenomenon of radiative neutron capture by uranium-235 and plutonium-239. According to these data, the radiative capture cross-section of plutonium-239 for slow neutrons was close to the fission cross-section. There were data proving the number of secondary neutrons at slow neutron-driven fission of plutonium-239 to be three. There was information that slow neutron absorption cross-section ddid not correspond to the $1/v$ law.

7. There were data on the neutron-uranium, -lead, -oxygen and -hydrogen interaction cross-sections.

8. There were data on the number of neutrons ($\nu = 2.6 \pm 0.5$) at spontaneous fission.

1945

9. Accurate cross-sections of uranium-235 and plutonium-239 fission driven by various-energy fast neutrons were received.

10. The data specified the values of critical radii for uranium-235 and plutonium-239.

11. Data were received on the number of secondary neutrons produced by fission.

12. Data were received on the process of spontaneous fission for plutonium-240.

13. Data were received on the detonation wave propagation scheme, reflector material deformation, explosion-driven compression of objects.

14. Data were received on the properties of plutonium in different phases and its compressibility.

15. Data were received on the fission cross-sections of uranium-235 and its applicability for the atomic bomb.

3.3. Isotope Separation

1941-1942

1. In Great Britain, in order to produce a material for the atomic bomb (uranium-235) it was recommended that uranium isotopes be separated using a diffusion facility.

As a source material for separation it was planned to use uranium hexafluoride, a chemically active substance, which complicated the process.

1943

2. According to the documents obtained from Great Britain, gas diffusion was the only reasonable way to separate uranium isotopes. The documents contained a detailed discussion of all components of a separation facility, which enabled development of our separation facility.

It surprised our specialists that one had preferred diffusion to the centrifuge method, because diffusion was considered practically inapplicable for isotope separation of heavy elements.

3. The documents received from Great Britain briefly discussed thermal diffusion, centrifugation and electromagnetic uranium isotope separation, which were characterized as the methods of low use for this purpose.

Analysis of the capabilities of these methods was conducted under the direction of Ya.B.Zeldovich, F.F.Lange, and L.A.Artsimovich.

4. According to the documents received from the United States, the method of gaseous diffusion involving uranium hexafluoride was considered the most suitable among several uranium isotope separation methods and the United States had begun construction of industrial facilities for these purposes.

1944

5. Data were received on using of fluorocarbons as lubricants in the separation facility and on the methods of their chemical synthesis.

6. Data were received on uranium metal reduction from uranium tetrafluoride.

3.4. Nuclear Reactors

1942-1943

1. Data from Great Britain were received on the chain reaction feasibility in natural uranium oxide (or uranium metal) mixed with heavy water.

I.V.Kurchatov wrote that information was surprising for our physicists as a result of inconsistent concepts of thermal neutron capture cross-section in heavy water. According to the data obtained by Yu.B.Khariton and Ya.B.Zeldovich, the chain reaction in the ‘uranium-heavy water’ mixture was possible, if the cross-section of thermal neutron capture by heavy hydrogen did not exceed $0.3{\cdot}10^{-26}$ cm^2. According to the published results of U.S. experiments, they had recourse to, this value was 10^{-26} cm^2; therefore, they drew a conclusion that the chain reaction in the ‘uranium-heavy water’ mixture was unfeasible (according to the present-day data, the cross-section of thermal neutron capture in deuterium is $0.06{\cdot}10^{-26}$ cm^2). In the USSS there were no such experimental data for lack of required amount of heavy water.

With regard to this information, I.V.Kurchatov pointed out the necessity to study non-uniform systems as potentially more promising ones with uranium concentrated in blocks in heavy water, and entrusted Yu.B.Khariton and Ya.B.Zeldovich with a task to conduct a comparative analysis of uniform and non-uniform systems.

2. There were data from Great Britain that it was possible to produce element-94 with mass number 239 in a uranium pile by capturing neutrons by uranium-238 to be used in the atomic bomb.

3. There were data from the United States on arranging heavy water production with the monthly output of 250 kg.

1944

4. There were data from the United States that it was feasible to build a reactor based on ordinary water and uranium metal.

5. There were data from the United States on the methods for uranium purification from neutron-absorptive impurities.

6. There were data from the United States on the ways to cool down a uranium-graphite pile – water and helium cooling.

7. There were data from the United States on the parameters of a uranium lattice in graphite, thermal neutron distribution and in-pile process control using boron or cadmium neutron absorbing rods.

8. There were data obtained about how much heavy water was required (3 to 4 tons) for a heavy water pile.

9. There were data obtained on the piles based on ordinary water and rods of uranium enriched in uranium-235.

3.5. Work Arrangement

1941

1. Activities to use uranium for military purposes had been conducted in France, Great Britain, the United States and Germany since 1939.

2. In 1941, the Military Cabinet of Great Britain established a Uranium Committee headed by G.P.Thomson to guide theoretical, experimental and applied studies in the area of atomic power utilization.

3. There were vast deposits of uranium ore in Canada, the Belgian Congo, the Sudety and Portugal.

4. In Great Britain, separation of uranium-235 from natural uranium was designated one of the key problems in the atomic bomb development.

5. The leaders of Great Britain considered the issue of military applicability of uranium-235 decided-in-principle. The efforts of prominent scientists, institutes and companies were combined within the framework of the uranium problem.

1942-1943

6. According to the documents from Great Britain, gaseous diffusion was considered the primary method for uranium isotope separation. This motivated supplementing the plan of separation studies by Laboratory 2 including the centrifuge method studies with diffusion-associated activities.

The capabilities of thermal diffusion, the centrifuge method and electromagnetic separation as applied to uranium isotopes were under evaluation at Laboratory 2.

7. At studying the documents from Great Britain, I.V.Kurchatov noted that they made them re-consider their concepts regarding a lot of aspects of the problem and determine areas novel for the Soviet physics:

- separation of uranium-235 by gaseous diffusion;
- gaining nuclear combustion in the ‘uranium-heavy water’ pile;
- studies of eka-osmium (plutonium) properties.

He also indicated that the entire body of the data pointed at the technical possibility of solving the complete problem much quicker than expected by our scientists who were not familiar with the progress abroad.

1945

8. There was information on building in the United States of

- Camp X, construction of a plant to produce U-235 in Woods Holl, Tennessee;
- Camp W, plutonium production in Hanford, Washington;
- Camp Y, a scientific and experimental site for atomic bomb development in Los Alamos, New Mexico.

9. Received was a list of leading scientists of Los Alamos involved in the development of the atomic bomb.

Appendix 1. Summary of the Report of L.P.Beria to I.V.Stalin (March 1942)

1. It was reported that since 1939 France, England, the United States and Germany had been involved in classified activities associated with military applications of uranium.

The English Military Committee had founded a Uranium Committee headed by prominent physicist G.P.Thomson to coordinate the efforts of English scientists in studying theoretical, experimental and applied aspects of atomic energy.

2. A promising material in the present connection was one of the isotopes of natural uranium (U-235), which was capable of efficient splitting.

There were vast deposits of uranium ore in Canada, the Belgian Congo, the Sudety and Portugal.

English scientists Prof. Rudolf Peierls and Dr. Bais developed a method for U-235 separation by means of a diffusion facility invented by Dr. Simon, which was recommended for the manufacture of the uranium bomb material. (Let us note that according to the earlier document received from Great Britain the source material for the isotope separation was chemically active uranium hexafluoride, which complicated operation of a separation facility.)

3. Professor Peierls theoretically estimated the critical mass of U-235 at 10 kg. (Let us note that according to the earlier document received from Great Britain the critical mass of U-235 lied between 10 and 43 kg, depending on the hypothesized fission cross-section of uranium, which was to be identified experimentally. The upper value of this range, which, for some reason, was missed in the report of L.P.Beria, is rather close to the actual critical mass value for U-235 metal of 50 kg.)

In the amount less than the critical value the substance was stable and safe, whereas, in a mass of the material greater than the critical mass there occurred a chain reaction of fission leading to an enormously powerful explosion.

As for the bomb design, its active part was to consist of two similar halves, whose integral mass was to be greater than the critical value. In order to produce a maximum-power explosion of these U-235 parts, their mass velocity was to be, according to Professor Fergusson, 6,000 feet per second (~1.8 km/sec). At lower velocities the chain reaction extinguished and explosion power reduced, the latter being, however, still much higher than that when a conventional explosive was used.

Professor Tailor calculated the effect caused by an explosion of 10 kg of U-235 to be equivalent to that of 1,600 tons of trinitrotoluene.

4. The major problems in the uranium bomb development were attributed to the separation of U-235 from other isotopes and attaining the required mass velocity.

5. The key conclusions were that the leaders of Great Britain considered the issue of military applicability of U-235 decided-in-principle; there was a preliminary theoretical foundation for designing and building a plant to manufacture uranium bombs, the efforts of prominent English scientists, institutes and companies were combined within the framework of the uranium problem.

6. Members of Academy P.L.Kapitza and D.V.Skobeltsyn and Professor A.A.Slutsky were declared specialists in the field of atomic nucleus fission in the USSR.

Appendix 2. Analysis of Data from Great Britain

On March 7, 1943, head of Laboratory 2 I.V.Kurchatov sent to M.G.Pervukhin a memo on the results of his analysis of documents received from Great Britain on the uranium problem. It was a sizeable document containing 14 pages and comprising sections discussing three subject areas: I. Isotope Separation. II. Nuclear Explosion and Burning. III. Fission Physics and Conclusion. On the whole, I.V.Kurchatov commented that getting this document was of ‘great, inestimable importance for our state and science’.

2.1. The most valuable part of the documents, according to I.V.Kurchatov, was that discussing the problem of uranium isotope separation.

According to the documents, the only reasonable way to solve the problem of isotope separation was to do this by means of diffusion through a barrier with small holes. As pointed out in the memo, our physicists and chemists were surprised with the fact that diffusion had been preferred to the centrifuge method, since our specialists considered diffusion practically inapplicable for the isotope separation of heavy elements. It was due to the data presented in the documents that our problem-related work plan was complemented with diffusion separation studies in addition to those of the centrifugal method (method of F.F.Lange).

I.V.Kurchatov pointed out that the documents presented a highly thorough study containing careful consideration of all components of a separation facility. In his opinion, by virtue of the data given in the documents after their verification and supplementing, the Soviet scientists would be able to develop and would develop a model of a diffusion separation facility.

In his memo, I.V.Kurchatov stressed that the documents contained a number of experimental data, as well as information about the work plan for making separation facilities and designing the separation plant. He pointed out that those data were less systematic and it would be desirable to get additional data, and specified a number of questions regarding the engineering layout of the separation facility.

The documents also summarized parameters of the thermal-diffusion, centrifuge and electromagnetic methods for uranium isotope separation, which were characterized as low-use methods as applied to the given task. I.V.Kurchatov pointed out that

- low efficiency of the thermal-diffusion method was verified by the calculations by Ya.B.Zeldovich conducted in compliance with his instructions in March 1943;
- efficiency of the centrifuge method could be evaluated after studying the equipment to be developed under the direction of F.F.Lange;
- correctness of the statement that the electromagnetic method was low-efficient was under check-out by L.A.Artsimovich.

2.2. I.V.Kurchatov found the second part of the documents important, as well.

First of all, this referred to the statement on the feasibility of the chain reaction in the mixture of natural uranium oxide (or uranium metal) with heavy water, since our specialists found surprising and conflicting with the common concept. The data presented in the documents were based on the experiments performed by scientists Hans von Halban and Lew Kowarski (1940), who had a lot of heavy water available and moved to Great Britain. I.V.Kurchatov explained the concept of the Soviet scientists to rest upon the calculated estimation of the maximum allowable cross-section of thermal neutron capture by deuterium nuclei at 3.10^{-27} cm^2 (Yu.B.Khariton, Ya.B.Zeldovich) and experimental cross-section value of 10^{-26} cm^2 published by U.S. scientists (group headed by Luis Alvarez) in 1940-1941. For lack of heavy water in the Soviet Union there were no own experimental data on the capture cross-section.

I.V.Kurchatov pointed out that the published uranium-moderator system studies had been conducted using uniform component mixtures and stressed the necessity to study non-uniform systems with uranium concentrated in the form of blocks in heavy water as potentially more promising ones. The comparative analysis was to be conducted by Yu.B.Khariton and Ya.B.Zeldovich.

I.V.Kurchatov highlighted very important comments given in the documents on the possibility of using as a bomb material of an element with the mass number 239 to be produced in a uranium pile at neutron capturing by nuclei of U-238.

2.3. As for the third section of the documents, I.V.Kurchatov pointed out the following aspects:

First, he stressed the fact of verification by Otto Frisch of the phenomenon of spontaneous uranium fission discovered by G.N.Flerov and K.A.Petrzhak, which made it impossible to concentrate uranium in a supercritical mass until the moment of explosion.

Second, he commented that the method of making an atomic bomb of two uranium parts discussed in the documents was not novel for the Soviet physicists and a similar approach had been proposed by G.N.Flerov.

Third, he pointed out that the documents presented data on the number of secondary neutrons (2 to 3 neutrons) per fission and contained a curve showing secondary neutron distribution as a function of energy. The documents, however, did not specify what neutrons (slow or fast) split nuclei. If the data referred to the fission of U-235 by slow neutrons, there was nothing new, because similar data had been published in 1939-1940. But if the data referred to the nuclear fission of uranium by fast neutrons, their significance was extremely high. Therefore, it seemed important to find out, what neutrons the data referred to, and get additional information on that crucial matter.

Fourth, he stressed significance of the data presented in the documents regarding the actual cross-sections of nuclear fission of U-235, $(2\text{-}3)\cdot 10^{-24}$ cm^2 in the energy range from 200 to 800 keV. It was important, because experimental data covered only a small range of neutron energies, whereas for a considerable range of neutron energies from 1 to 1,000 keV theoretical dependencies provided discrepant results.

Appendix 3. Production of Transuranium Elements in a Uranium Pile

On March 22, 1943, I.V.Kurchatov sent M.G.Pervukhin a memo describing a new approach to the uranium bomb development problem. This event proved to be one of the most crucial points in the development of the Soviet atomic bomb.

3.1. I.V.Kurchatov pointed out that the intelligence reports under analysis contained desultory remarks on the possibility of using in a uranium pile of not only U-235, but also of U-238 and potential application of combustion products of U-238 for the bomb instead of U-235. In this connection, I.V.Kurchatov thoroughly studied the latest papers on transuranium elements (eka-rhenium-239 and eka-osmium-239) published by U.S. specialists and identified a new direction in dealing with the entire problem attributed to the peculiarities of transuranium elements.

3.2. I.V.Kurchatov studied the succession of neutron captures by nuclei of U-238, which produced in turn an unstable nucleus of U-239 (lifetime ~ 20 min) to transform into likewise unstable (lifetime ~ 48 hours) eka-rhenium (neptunium-239) followed by eka-osmium (plutonium-239), which would live for a long time period and accumulate in a uranium pile.

Theoretically, hit by a neutron, a nucleus of eka-osmium was to split and release secondary neutrons; thus, in that regard it was to be equivalent to U-235. If it was actually so, it should be feasible to separate eka-osmium from the uranium pile and use it to build an eka-osmium bomb. If that could solve the problem, there was no necessity to separate uranium isotopes.

3.3. According to I.V.Kurchatov, that approach to the problem could be implemented if

- there was a uranium pile constructed based on natural uranium;
- if properties of eka-osmium and U-235 were similar.

Further, he wrote that in the USSS there had been no activities performed as applied to eka-rhenium-239 and eka-osmium-239. The major efforts in that area were implemented under the leadership of Edwin McMillan who had at his disposal the world’s most powerful cyclotron located at the laboratory of Ernest Lawrence at Berkeley, California. According to his latest publication of 1940, Edwin McMillan obtained eka-osmium-239 in the amount sufficient to study its properties. In the USSR, it was impossible to study its properties until 1944, when our cyclotrons were reconstructed and put into operation. He pointed out that the issue on the possibility of some preliminary investigations was to be discussed with V.G.Khlopin and G.N.Flerov as early as in 1943.

3.4. I.V.Kurchatov suggested entrusting intelligence agencies with the task to find out what had been accomplished in this area in the United States. To be cleared up were the following questions:

- What neutrons, fast or slow, split nuclei of eka-osmium-239?
- If fission occurred, what was the fission cross-section (individually for fast and for slow neutrons)?
- Was there spontaneous fission of eka-osmium-239 and what was the half-life?
- What time-dependent transformations happened to eka-osmium-239?
- What was the scope of work as applied to cyclotron facilities?

I.V.Kurchatov mentioned that he had discussed the above ideas with A.I.Alikhanov and I.K.Kikoin and that detailed quantitative analysis of the progress would be entrusted to Ya.B.Zeldovich.

Appendix 4. Studying the List of U.S. Uranium Efforts

Not later than in June 1943 there were received intelligence reports containing a list of 286 projects (with titles and, in some cases, abstracts) of U.S. scientists on the uranium problem. I.V.Kurchatov analyzed this list and on July 3, 1943 reported the results of his analysis in a memo to M.G.Pervukhin. In this memo he drew particular attention to the aspects, data on which would be useful. He also suggested familiarization with the analysis results of S.V.Kaftanov (representative of the State Defense Committee for science) and G.D.Ovakimyan (head of Division 1 of the NKGB Directorate).

4.1. First, I.V.Kurchatov distinguished 29 projects on uranium isotope separation by diffusion. He wrote that Americans must have made progress in that area and that it would be highly valuable to get detailed technical data on those projects. He drew a conclusion that Americans were devising a facility with a few stages as distinct from the multi-stage English facility.

4.2. There were 18 projects on the centrifuge method for isotope separation. I.V.Kurchatov pointed out that the results of those efforts were absolutely unknown in the Soviet Union and that those projects involved eminent scientists. He attributed the importance of getting additional information on that matter to the necessity of proving, whether the negative conclusion on the capabilities of that isotope separation method as presented in the English documents was correct. Laboratory 2 (I.K.Kikoin) studied that separation method using a facility proposed by F.F.Lange and built in Ufa.

4.3. Ten projects were distinguished on the feasibility of a uranium-235 bomb. I.V.Kurchatov stressed that almost all of those projects were of great interest for them. Similar efforts were under way in the USSR and it was very important to compare those with the U.S. projects, since our results strongly differed from those given in the English documents. That, first of all, referred to the fission of U-235 by middle-energy neutrons. According to the English documents, for neutrons with the energy of several hundreds of thousands of electron-volts, the fission cross-section of U-235 was (2-3)$\cdot 10^{-24}$ cm^2, whereas according to G.N.Flerov and K.A.Petrzhak, in that range it was to be not higher than 10^{-25} cm^2. (Let us note, that the actual fission cross-section of U-235 in this range is approximately $1.25\cdot 10^{-24}$ cm^2).

That issue was fundamentally important, since it was critical for the size of a U-235 bomb and the feasibility of a uranium metal pile.

In this connection I.V.Kurchatov wrote that it was important to learn about

- Breit's comments on the research project of Briggs and Heidenberg on U-235 fission by middle-energy neutrons;
- Marshall's and Szilard's investigation into photoneutron capture by uranium;
- Szilard's and Cinn's study of inelastic neutron scattering by uranium and other heavy elements;
- the outcome of Bennet's and Richards's research project on the spectrum of secondary neutrons from U-235;
- results of Marshall's and Szilard's study of fission driven by secondary neutrons.

I.V.Kurchatov also highlighted a project of Kennedy and Segre on the spontaneous fission of uranium. He wrote that G.N.Flerov and K.A.Petrzhak had discovered this phenomenon in 1940 in the Soviet Union, but a publication on that effort had been left without response from abroad. According to the English documents of Otto Frish, spontaneous fission had been observed in England, but because of the absence of isotope separation he, like Flerov and Petrzhak, had failed to identify, what uranium isotope the spontaneous fission was to be ascribed to. As could be seen from the documents, Kennedy and Segre had coped with that task.

4.4. There were 32 projects on the piles using uranium and heavy water. I.V.Kurchatov pointed out the U.S. to carry on intensive investigations associated with the piles using uranium and heavy water. Particular emphasis in the projects was given to various methods for heavy water production. By that time there had been no such projects in the Soviet Union and those were to be set about by the Ukrainian Academy of Sciences, whose laboratories could recommence pre-war heavy water production studies.

The documents also mentioned Lawrence's project on slow neutron capture by deuterium, the results of which were of tremendous interest, since that process determined the pile feasibility itself. It was be extremely important to get data on the methods and results of that investigation.

4.5. Twenty nine projects were distinguished on the uranium-graphite piles.

I.V.Kurchatov noted that major results of the U.S. projects on the uranium-graphite piles were known to them by virtue of the documents received from the United States. Those documents, however, only outlined the general outcome and contained no significant technical details, studying which required a tremendous amount of effort of numerous specialists in various areas. One could point out, that in the United States that project involved such details, which were typical of a technical project, rather than of an abstract study. That proved the efforts of the U.S. scientists in making uranium-graphite piles real to be serious. Getting detailed technical documents on that system was extremely necessary (the United States commissioned its uranium-graphite reactor on December 2, 1942).

4.6. There were 14 projects on elements 93 and 94.

I.V.Kurchatov pointed out the documents received from the United States to contain rather detailed data on the physical properties of elements 93 and 94: decay nature, energy of emitted particles, half-life, cross-section of fission by slow neutrons and others. Of special interest was the project of Seaborg and Segre on the nuclear fission of eka-osmium (94-239) driven by fast neutrons. In terms of its response to the neutron impact, that element was similar to uranium-235, whose fast neutron-driven fission was unexplored there so far. The data of Seaborg on eka-osmium 94-239 were, consequently, of interest also as applied to the problem of U-235 bomb feasibility.

In June 1943 the task of studying the chemistry of elements 93 and 94 was entrusted to B.V.Kurchatov.

4.7. There were 30 projects on the general issues of neutronics.

As pointed out by I.V.Kurchatov, the projects in that area were of great interest, even though most of the directions had been rather well developed in the Soviet Union during the last six months. That, first of all, referred to the neutron deceleration. Laboratory 2 was versed in that subject due to the efforts of Yu.B.Khariton, Ya.B.Zeldovich and I.Ya.Pomeranchuk carried on in 1943. However, lately they had faced a number of difficulties, which, supposedly, were successfully dealt with in Teller's study of the netlike structure's influence on the exponential neutron density variation in a pile. A number of projects contained a list of constants that had been earlier under estimation both in the Soviet Union and abroad, but for their project's purposes it was important to know the latest results.

4.8. There were 55 uranium chemistry projects.

I.V.Kurchatov noted most of the projects to be devoted to the methods for uranium metal and its oxide production and their purity analysis methods. At that, particular attention was given to the separation from uranium oxide of rare earth elements and boron. Such attention was explicable, because those impurities had extremely high slow neutron absorption cross-sections and in trace concentrations might cause chain process evolution in a uranium pile.

Further, he wrote that in the documents received earlier from the United States there were references to more efficient purification methods, which were, however, of no special interest for our chemists. For example, uranium oxide, whose commercial production had been set up, completely satisfied the criteria specified by V.G.Khlopin based on the requirement for the thermal neutron absorption by impurities not to exceed 10% of neutron absorption by uranium itself.

The other group of documents dealt with the chemistry of uranium hexafluoride (production ways and properties), being of special value for all isotope separation flows. We also were going to conduct such investigations and those were included into the work schedule of RIAN and the team of V.I.Spitsyn, Moscow State University.

A number of documents discussed the chemistry of new uranium compounds (organometallic, volatile, etc.). Getting data on this subject was of great interest for our chemists.

4.9. Among the general conclusions, I.V.Kurchatov pointed out that in the United States uranium-related projects were enjoying rapid progress. The Soviet uranium project comprised (not in the entire scope, of course) most of the directions, which were under development within the U.S. uranium project.

He pointed out that as to the problem of the pile using uranium and heavy water, in the Soviet Union there had been no activities commenced so far, while it required considerable attention. Making that type of pile was somewhat more difficult as compared with the uranium-graphite pile because we had no necessary heavy water production. Besides, that pile did not allow high temperature rises and its operation would be complicated by radiation-driven water decomposition. That system, however, had one significant advantage as against the uranium-graphite pile, because its building required 1-2 t, instead of 50 t, of uranium. Such an amount would be available as early as in 1943, whereas it was unclear how long it would take our country to pile 50 t of uranium.

Appendix 5. Activities Under the Uranium Project

In April 1943 division head of the First Directorate of NKGB G.D.Ovakimyan issued a memo on the utilization of atomic energy. This report summarized uranium problem-related activities in the United States, Great Britain and, to some extent, Germany.

U.S. projects were pointed out to have the widest scope and to be the most successful. In the United States there had been operating a 'uranium pile'. Carbon, heavy water and beryllium were proved to be most suitable moderators. Carbon in the form of grafite was eventually chosen as the moderator. The mass of carbon in a 'uranium pile' will be from six to eight times higher than the mass of uranium. The total mass of carbon and uranium in the 'uranium pile' will be from 400 to 600 tons. During the reaction, element-94, whose properties were similar to those of U-235, piled up. Separated U-235 or element-94 produced in a uranium pile were to be used as bomb materials. Coefficient of neutron multiplication would substantially encrease if uranium and the moderator presented a heterogeneous structure.

Operation of the pile was pointed out to allow gaining experience and piling materials to produce radioactive combat means.

Appendix 6. Analysis of the Review Data

On December 24, 1944 I.V.Kurchatov issued a summary of the Uranium Problem Review received by the intelligence services.

1. He pointed out the review to be an excellent collection of the latest data on the basic theoretical and conceptual lines of the problem. Most of the data were familiar to them due to the documents received in summer 1944. The review however contained two new crucial remarks of principal value:

1. On the feasibility of a pile using ordinary water and uranium metal.
2. On the availability of radiative neutron capture by uranium-235 and plutonium-239 and deviation from the 1/*v* law at slow neutron absorption.

2. A pile using ordinary water and uranium metal had formerly been considered unfeasible, since in compliance with the earlier received English documents, neutron breeding coefficient K for this system was known to be 0.95. The transition to a heterogeneous system could result in the growth of K up to the value more than 1, but one could find it out only having at one's disposal a considerable amount of uranium metal. We were not able to perform such an experiment at that time.

Since implementing a system with ordinary water and uranium metal essentially facilitated meeting the challenge of building a pile and, consequently, manufacturing plutonium, it was extremely important to get such information on that system.

3. Based on some experiments performed at Laboratory 2 one could draw a conclusion that absorption of slow neutrons by uranium-235 did not satisfy the 1/v law. The review contained references to that and to the presence of radiative neutron capture by uranium-235 and plutonium-239. It seemed surprising that radiative capture cross-section of plutonium-239 was approximately as high as the fission cross-section of that isotope. It was important to get more detailed data on that subject and learn about experimental setup used to establish that 3 neutrons were produced in a fission of plutonium atom driven by a thermal neutron.

4. Of interest was a remark on the investigations into various physical properties (fission, elastic and inelastic scattering) of uranium-235 and plutonium in the context of bomb building. It was very useful to find out how those investigations had been arranged and what results had been obtained.

Appendix 7. U.S. Atomic Bomb Development

On February 28, 1945 People's Commissar for State Security V.N.Merkulov sent a memo to L.P.Beria on the status of the U.S. atomic bomb development project. L.P.Beria appreciated this information.

1. The memo pointed out that the efforts carried out by the leading scientists of England and the United States on studying the atomic bomb feasibility had demonstrated that type of weapons to be worth considering feasible and the problem as it was then to be restricted to two tasks:

- production of the required amount of fissionable materials – uranium-235 and plutonium;
- design study of bomb detonation.

To respond to those two tasks in the United States there had been established the following centers:

- Camp X (Woods Holl, Tennessee): construction of a plant to produce U-235;
- Camp W (Hanford, Washington): plutonium production;
- Camp Y (Los Alamos, New Mexico): scientific and experimental investigations associated with atomic bomb development.

2. Rated energy release of a bomb with a total weight of about 3 t was equivalent to the energy produced by 2,000 to 10,000 t of explosive.

An atomic explosion was to entail not only a blast wave, but also high temperature and a tremendous radioactive effect resulting in the annihilation of all living things within a radius of up to 1 km.

3. Two ways of producing an atomic bomb explosion were under development:

- ballistic (gun principle);
- inward explosion (implosion).

Production of the first bomb was supposed to take at least 1 year and 5 years at most.

As for the bombs of somewhat lower yield, one could expect one or two bombs, for which Americans had enough active material, to be built in a couple of weeks. The first trial explosion was to be conducted in 2 or 3 months.

Appendix 8. Analysis of Data Received from the United States

On March 7, 1945, I.V.Kurchatov prepared the report on the newly arrived intelligence.

In his report I.V.Kurchatov evaluated the data on the use of “inward explosion” (implosion) in making the atomic bomb. He noted that it was difficult to definitely say what conclusion had been drawn in the documents under analysis (and that that method was to be preferred to the method based on the gun principle), but it was beyond doubt that implosion was of great interest, correct in principle and was to undergo thorough theoretical and experimental evaluation.

I.V.Kurchatov pointed out the documents to contain interesting comments on the insulation material for the atomic bomb (discussed in the neutron reflector surrounding the fissionable material). Those agreed with the concepts that had lately been advanced in our country. Our devices were also to use beryllium as an insulator, but in the form of metal as contrasted to its oxide, as specified in the documents under discussion.

Appendix 9. Analysis of Data Received from the United States

On April 7, 1945 I.V.Kurchatov made a review of newly received data on the properties of nuclear materials, specific features of the implosion-based atomic bomb and electromagnetic separation of uranium isotopes.

1. As for the properties of nuclear materials, he pointed to the value of a table of accurate fission cross-sections of uranium-235 and plutonium-239 split by various-energy neutrons, which made it possible to reliably identify critical dimensions of the atomic bomb. Owing to this, one could recognize the critical radius formulas given in the documents as correct with the accuracy of up to 2%, as specified in the documents. Along with that, it remained unclear how such a high accuracy in establishing fission cross-sections could be achieved and it was essential to get data on the neutron breeding experiments that had been conducted with a substantial amount of uranium-235 or plutonium. (One can assume that these data gave rise to a basic revision of our specialists' concepts on the critical mass of fissionable materials, namely, uranium-235.)

The documents contained data on the number υ of secondary neutrons produced at fission. The review pointed out that the documents did not clearly indicate what neutrons (fast or slow) were characterized by $\nu = 2.47$ for uranium-235 and that there were no data on ν for fission of uranium-238 by fast neutrons.

The same section stressed the significance of data received on spontaneous fission of heavy nuclei, and surprisingly high probability of that process for plutonium-240 inter alia.

2. The other section of the documents described the implosion-based bomb detonation method, about which I.V.Kurchatov wrote that we had learnt about that method quite recently and were just at the beginning of dealing with it. In this commentary he wrote that we had already evaluated all its advantages as against the gun principle. The documents received contained: 1) a scheme of detonation wave propagation in the explosive and reflector's material deformation; 2) description of explosion-driven compression of an object and explosion itself. I.V.Kurchatov emphasized the importance of these documents with particular stress on the conditions that enabled making the explosion effect symmetric, which was necessitated by the method's nature itself. He wrote that the documents gave account of very interesting phenomena caused by non-uniform detonation wave effects and suggested that such non-uniformity might be precluded by proper positioning of detonators using high explosive interlayers of various action. The documents also discussed experimental techniques as applied to explosives and optics of explosion phenomena.

In conclusion he wrote that because our studies of that method were by far not advanced it was impossible to formulate the issues that needed further details to be found out, but it could be done later after a serious analysis of the documents. For this purpose he considered it necessary to let Yu.B.Khariton acquaint himself with the documents. From these considerations on April 30, 1945 I.V.Kurchatov sent G.D.Ovakimyan a request for such authorization.

3. As for the data on the electromagnetic isotope separation method, U.S. experiments were pointed out to involve uranium hexafluoride and the method to have something in common with our scheme, tests of which had just begun.

Appendix 10. Analysis of Data Received from the United States

On April 11, 1945, I.V.Kurchatov prepared a report analyzing a number of documents provided by the intelligence in late 1944 and presenting multidisciplinary data on the U.S. atomic project as of different time points. He divided the documents into the following groups: technology and chemistry; uranium-plutonium pile; pile using uranium and heavy water; activities of one of the U.S. laboratories in 1943 through 1944; miscellaneous projects.

1. As applied to the uranium-graphite pile problem, there were discussed two systems: water-cooled and helium-cooled. I.V.Kurchatov pointed out the water-cooled pile to be a less sophisticated technical form of pile implementation. At that time, this system was not developed here since there was no confidence that due to the neutron absorption by water the breeding coefficient was higher than 1. Such a risk and other difficulties were also stressed in the documents dated 1942. I.V.Kurchatov pointed out that it was essential to learn about the progress in that area and find out whether corresponding activities had been resumed.

As for the helium-cooled system, there were no basically new remarks, since earlier there had been received later documents. Along with that, of interest were parameters of the uranium array embedded in graphite, computations and experiments on thermal neutron distribution in uranium spheres and cylinders, experiments on fission product diffusion from glowing uranium, and a theoretical report on in-pile process control using boron or cadmium rods with high neutron absorbing capacity. To judge by the data provided, a high-power pile of that type was to have been commissioned in 1943 and was to be operating at that time.

2. As for the heavy water pile, there were data that the minimum amount of heavy water in the pile was to make 3 to 4 tons.

Appendix 11. Parameters of the U.S. Atomic Bomb

On July 6, 1945 People’s Commissar for State Security of the Soviet Union V.N.Merkulov sent L.P.Beria a letter saying that according to the data received from several reliable intelligence sources, in the U.S. the first experimental atomic bomb explosion was scheduled for June 1945. The explosion was expected to take place on July 10 (Trinity tests took place on July 16, 1945).

The letter pointed the atomic bomb to be made of plutonium produced in uranium piles in the form of a 5-kg ball. In its center there was an initiator, a beryllium-polonium source, which ignited the active material at a proper moment. Plutonium was encased in an aluminum 11-mm-thick shell, which in turn was surrounded by a 46-cm-thick HE envelope. The total weight of the bomb was about 3 t, and the anticipated yield was equivalent to 5,000 tons of TNT (official yield of that explosion made 21 kt, i.e. about 4 times as high as expected).

As for the active material supply for bomb building, the same documents reported that

- as of April 1945, the United States had 25 kg of uranium-235 and were producing 7.5 kg per month;
- in Los Alamos they had 6.5 kg of plutonium, its production in the piles had been arranged and proceeded ahead of schedule.

On July 9 the documents on these issues giving further details were submitted to I.V.Kurchatov. It was pointed out that plutonium was surrounded by 50 pounds of uranium, only then followed by the aluminum envelope. The bomb housing’s internal diameter was 140 cm. The efficiency of the bomb was (5-6)% (i.e. at a nuclear explosion 5 kg of Pu fissioned down to 0.3 kg of Pu).

Appendix 12. Design of the U.S. Atomic Bomb

On October 18, 1945, People’s Commissar for State Security V.N.Merkulov sent L.P.Beria a report on the U.S. atomic bomb design that had been drawn up based on the intelligence gathered by the NKGB of the Soviet Union (the report was signed by NKGB colonel L.Vassilevsky). According to these documents, the bomb was a pear-shaped device with the maximum diameter of 127 mm, the length (including a stabilizer) of 325 cv and the weight of 4,500 kg. The bomb consisted of the following parts:

- initiator;

- fissile material;
- tamper;
- aluminum shell;
- high explosive;
- lenses containing high explosive;
- detonating device;
- duraluminum layer;
- armored steel housing;
- stabilizer.

All the bomb parts, except for the stabilizer, the detonating device and the steel housing were hollow spheres inserted in each other.

1. The urchin-type initiator was a polonium-beryllium system with a 1-cm radius. The total amount of polonium was 50 Ci. The flow of neutrons was driven by an impact produced by the detonation of the bomb's high explosive towards the initiator, which resulted in the interaction of polonium α-particles with beryllium nuclei.

2. The bomb's active material was a sphere of the δ-phase of plutonium with a 15.8 kg/cm^3 specific weight consisting of two halves pressed with each other. There was a 0.1-mm thick golden layer between the two hemispheres, which protected the initiator from high-velocity jets moving along the joint plane of the hemispheres of active material, which could untimely fire the initiator. There was a hole with a 25-mm diameter in one of the hemispheres to insert the initiator, which was sealed afterwards with a plutonium plug. The outer diameter of the ball was 80-90 mm.

3. The tamper was a uranium metal sphere with a 230-mm outer diameter. There was a hole for active material insertion, which was sealed with a uranium metal plug. The tamper reduced the amount of the active material necessary to build the atomic bomb. The outer surface of the tamper was coated with boron, which absorbed thermal neutrons that escaped from radioactive substances and could cause premature disruption.

4. Aluminum shell.

The aluminum shell that surrounded the tamper was a sphere with a 460-mm outer diameter made of two halves, which were fixed together by means of grooves and flanges. One of the hemispheres had a hole for active material insertion that was sealed with an aluminum plug. The purpose of the shell was to ensure uniform transmission of pressure produced by the HE explosion towards the center of the bomb.

5. HE layer and lenses.

Next to the aluminum shell there was a layer of HE, consisting of 32 specially shaped chunks. The internal facing-the-center surface of the chunks was spherical with a diameter equal to the diameter of the aluminum shell. There were special cavities on the external surface of the HE chunks with a shape such as to fit 20 hexagonal and 12 pentagonal lenses. Each lens consisted of two types of HE, one of which was-burning, and the other was slowly-burning. When lens was positioned, the fast-burning segment came into contact with the HE layer. The total weight of HE was about 2 t.

Each lens was wired to one detonator, which was provided with two electric fuses to produce the explosion simultaneously in a more reliable manner.

6. Duraluminum shell.

The HE layer and the lenses were encased in a duraluminum shell wired to the 180-kg detonating device. The internal diameter of the shell was about 1,400 mm, and its weight together with the detonating device was about 700 kg.

7. Bomb assembly.

The uranium metal ball was inserted in the aluminum sphere with adequately fitted holes. HE blocks with lenses were mounted on the outer aluminum surface, except for one located right above the hole. The lenses were attached to the duraluminum shell, to which was also fastened the detonating device. The bomb was then ready for transportation. Since plutonium and radioactive material of the initiator self-heated up to the temperature 90$^{\hat{\imath}}$Ñ higher than the ambient temperature, they were brought to the point of final assembling in special cooled containers. Further, the initiator was inserted in the plutonium sphere, which was put into the tamper. The plugs were placed, the last chunk of HE was mounted and the hole in the outer duraluminum and steel casings was sealed.

8. Somewhat later a review concerning the U.S. atomic bomb drawn up by Ya.P.Terletsky provided additional and clarifying data. The documents he studied described the Trinity atomic bomb, contained data on the bombs dropped in Hiroshima and Nagasaki and discussed test results. The Hiroshima bomb was noted to be a gun-type device using uranium-235, and the Nagasaki bomb was pointed out to be an implosion-type plutonium device. The documents gave a detailed account of the Trinity blast, the results of measurements of the bomb’s destructive effects and total yield, radiation intensity, post-explosion radioactivity, time span between detonators’ disruption and the outset of the chain reaction. The documents expounded the theory of shock wave propagation, gave expressions for pressure and density distributions in an explosion pulse for various cases.

The data provided also characterized the changes in the critical mass, properties of different phases of plutonium and its compression, fission cross-sections of uranium-233 and discussed bombs using plutonium and uranium-233.

Chapter 2

Development of the Early Nuclear and Thermonuclear Weapons

Contents

1. Development and Testing of the First Soviet Atomic Bomb

1.1. Establishing the Major Agencies for the Soviet Atomic Weapons Development

On August 20, 1945, the State Defense Committee issued resolution #9887 establishing the Special Committee to manage the nuclear project on behalf of the state. The resolution of I.V.Stalin named L.P.Beria leader of the committee and B.L.Vannikov, People's Commissar for Munitions (retaining this position) his deputy. The committee also included G.M.Malenkov, N.A.Voznesensky, A.P.Zavenyagin, I.V.Kurchatov, P.L.Kapitza, M.G.Pervukhin and V.A.Makhnev (secretary). Along with this, there was appointed a Technical Board headed by B.L.Vannikov. Members of the board were A.I.Alikhanov, I.N.Voznesensky, A.P.Zavenyagin, A.F.Ioffe, P.L.Kapitza, I.K.Kikoin, I.V.Kurchatov, V.A.Makhnev, Yu.B.Khariton and V.G.Khlopin.

Late summer 1945 was a real turning point in the Soviet atomic program. After establishing the Special Committee, on August 30, 1945 the Council of People's Commissars adopted resolution 2227-567 establishing the First Main Directorate of the SNK SSSR (PGU). This resolution provided for the necessary development of the organizational structure of the atomic project, which since then had a body with executive, intermediary and routine managerial functions. B.L.Vannikov was appointed Head of the PGU. Deputy heads of the PGU were A.P.Zavenyagin, Deputy People's Commissar of Internal Affairs of the Soviet Union; N.A.Borisov, Deputy Chairman of the State Planning Committee of the Soviet Union; P.Ya.Antropov, State Defense Committee officer, head of the Second Main Directorate in future; A.G.Kasatkin, Deputy People's Commissar of Chemical Industry. Later, leaders of the PGU became V.S.Emelianov, Deputy People's Commissar of Metallurgy Industry; A.N.Komarovsky, Head of the Directorate for Industrial Construction (Glavpromstroi) of the People's Commissariat of Internal Affairs of the Soviet Union; E.P.Slavsky, Deputy People's Commissar of Nonferrous Metallurgy; A.M.Petrosiants, State Defense Committee officer; A.S.Aleksandrov, Assistant Deputy Chairman of the Council of People's Commissars and Council of Ministers of the Soviet Union.

The Technical Board worked at the PGU and included, along with B.L.Vannikov and A.P.Zavenyagin, atomic experts I.V.Kurchatov, A.I.Alikhanov, A.F.Ioffe, P.L.Kapitza, Yu.B.Khariton. Later there were established other boards for particular research and production problems and directions.

A notable role in the creation of the scientific foundation for the Soviet nuclear weapons development was played by the efforts of the Soviet intelligence, which managed to gather and transfer various valuable data on both basic concepts and specific scientific and technical atomic project-related information.

One of the first practical steps of the Special Committee and the PGU were resolutions providing for the development of industrial facilities for the nuclear weapons complex. 1946 saw a number of crucial solutions associated with these intentions. One of them referred to establishing at Laboratory 2 of a special design bureau to develop nuclear weapons.

On April 9, 1946 the Council of Ministers of the Soviet Union adopted classified resolution 806-327 establishing KB-11. This was the name of the institute to design a new “device”, i.e. atomic bomb.

The above resolution also named leaders of KB-11. P.M.Zernov was appointed its Head and Yu.B.Khariton its Chief Designer.

By the moment of adopting the resolution, the issue regarding KB-11 creation had been studied in every detail. Its location had been identified taking into account the specific character of its future work.

On the one hand, the top-secrecy of projected activities and the necessity of blasting experiments predetermined the choice of a sparsely populated, protected from visual examination region. On the other hand, it could not be located at a too far distance from enterprises and institutes, which participated in the atomic project, and most of which were located in the central regions of the country. Of no small importance was availability in the territory selected for the KB of industrial and transportation facilities.

Along with the resolutions related to the organization and construction of KB-11, respective documents also specified objectives in the area of research and production. KB-11 was entrusted with the task to devise two versions of atomic bombs – a plutonium one using spherical compression and one with uranium (U-235) based on the gun principle. Upon development completion it was planned to perform state tests of the devices at a special testing ground. The surface detonation of the plutonium bomb was originally to be conducted before January 1, 1948 and that of the uranium bomb before June 1, 1948. There were also to be tested nuclear devices to be dropped from an airplane in the form of an air bomb with two types of warheads. The tests of the air atomic bombs were to be preceded by their flight tests without warheads by dropping from an airplane of five mock-ups of each bomb type. The first five mock-ups of the plutonium and the uranium bombs were to be made by March 1, 1948 and January 1, 1949, respectively.

As the formal starting point of the development of the RDS-1 one should recognize the date of issue of a Tactical and Technical Order (TTZ) for Atomic Bomb Development signed by Chief Designer Yu.B.Khariton on July 1, 1946 and submitted to B.L.Vannikov, Head of the First Main Directorate of the Council of Ministers of the Soviet Union.

The technical order consisted of 9 items and specified the type of nuclear fuel, the way of its transfer through the critical state, dimensions and mass of the atomic bomb, electric detonators' firing diversity, requirements to the altitude initiator and self-destruction of the device in case of failure of equipment that ensured operation of the initiator.

The TTZ provided for the development of two types of atomic bombs – an implosion-type plutonium and a gun-type uranium one. The bomb was to be at the most 5 m long, have a 1.5-m diameter and weight 5 tons.

At the same time, it made provisions for constructing a testing ground, an airdrome, a pilot plant, as well as arranging medical services, creation of a library, etc.

The governmental edict on creating KB-11 of June 21, 1946 provided for issuing the Atomic Bomb TTZ before July 1 that year, and developing its main parts before July 1, 1947.

In addition, in 1946, there were issued task orders for spark or bridge-type electric fuses, air bomb casing and a radio sensor.

The task order for the HE charge was placed in May 1946 and provided for the development of a composite charge of 30-40 chunks to make a hollow sphere when assembled.

1.2. Major Problems in the Development of the First Soviet Atomic Bomb

Atomic bomb development necessitated dealing with an extra-wide range of physical and technical problems associated with an extensive program including theoretical and computational studies, design activities and experiments.

First of all, to be studied were physical and chemical properties of fissionable materials, and to be tested and verified were the methods for their casting and machining.

It was necessary to develop radiochemical methods to extract various fission products, arrange polonium production and develop a neutron source fabrication technology.

Demanded were techniques to identify the critical mass and theories of efficiency and nuclear explosion on the whole.

A separate segment of extensive investigations was associated with the converging detonation wave theory, HE detonation and processes at the detonation front at detonation motion from one explosive to another and collision of detonation waves originating in different points.

It was impossible to do without studies of metals’ compressibility at high pressures and splintering phenomena.

It was necessary to develop lab-scale methods to study gas-dynamic processes at spherical HE charge detonation and methods to measure nuclear explosion parameters during ground tests.

Challenging were the tasks associated with the development of special electric fuses, automation tools, air bomb casing, optimization of its ballistics and development of suspension parts and instrumentation for transients studies. Finally, a considerable number of problems were to be addressed as to the construction of a special nuclear testing ground.

The above brief list of areas, in which activities were set off, comprises by far not the entire scope of activities that were to be implemented to successfully fulfill the atomic project.

Taking into account the problems to be addressed by KB-11, there was established an order of priority in forming its main structural divisions. First of all, there were created laboratories of HE, radiography, neutronics, for explosion efficiency studies, quality control of fission materials (plutonium and uranium) and for their metallurgy and machining.

Resolution of the Council of Ministers of the Soviet Union dated February 8, 1948 that revised the date of the atomic project’s main task completion charged Yu.B.Khariton and P.M.Zernov with ensuring production and presentation of the completed RDS-1 atomic bomb with munitions for the state tests by March 1, 1949.

In order to ensure timely fulfillment of the task, the resolution specified the scope and completion dates of research projects and fabrication of facilities for flight tests, as well as of decision-making on individual organizational and staff-related issues.

Among the research projects distinguished were the following:

- completion before May 1948 of spherical HE charge development;
- completion of studies of metals compression at HE detonation before July;
- neutron initiator development completion before January 1949;
- identification of the critical mass and assembling of plutonium and uranium warheads for RDS-1 and RDS-2. Providing for the RDS-1 plutonium warhead assembling before February 1, 1949.

Designing the atomic device itself, named RDS-1, was started in late 1945, that is, before the creation of KB-11. The development began from a model with the size five times as small as the actual one. The project was implemented without task order according to oral instructions of Yu.B.Khariton. The first sketches were made by N.A.Terletsky, who worked at Research Institute 6 (NII-6) in a separate room, the right of access to which was given only to Yu.B.Khariton and E.M.Adaskin, Deputy Director of NII-6, who provided general coordination of the project with other teams that had started fast-action detonator development to ensure simultaneous firing of a series of electric fuses and electric firing studies. A separate group was charged with selecting HE and technologies to fabricate unconventionally shaped parts of explosives.

Early in 1946, the mock-up was developed and before summer fabricated in duplicate. The mock-up was tested at a testing ground of NII-6 in Sofrino.

Towards the end of 1946 there began preparation of documents for the actual warhead, whose development had been started at KB-11, where early in 1947 in Sarov were created minimum conditions for parts fabrication and blasting operations (until Factory 2 was commissioned at KB-2, HE parts were delivered from NII-6).

By the moment as they began the atomic warhead development, our physicists were to some extent ready for working in the area of nuclear warhead development (due to their previous activities), whereas for designers this area was absolutely new. They were not familiar with the physical principles of warheads, new materials to be used in the device, their mechanical properties, admissibility of their keeping together, etc.

The design of the warhead was made such as to take into account home engineering capabilities and meet the requirements to strength and performance as determined by our conditions.

With the initial arrangement of parts development, when the project involved institutes and enterprises controlled by different agencies, there was a problem related to the fact that all documents were prepared to satisfy different agency-specific guidelines (instructions, specifications, standards, drawing convention, etc.). This by far complicated the development, since requirements to the device parts to be produced differed a lot. The situation improved in 1948-1949, when N.L.Dukhov was appointed Deputy Chief Designer and Head of Scientific and Design Department of KB-11. From OKB-700, Chelyabinsk he brought a Drawing System adopted there and arranged revision of earlier developed documents, thus putting these in order. The new system matched the conditions of the unusual development providing for multi-choice design studies.

As for the radio- and electrotechnical parts of the device (RDS-1), they all were of home manufacture. At that, they were developed in a manner such as to ensure redundancy of the most critical components (for reliability purposes) and allow for miniaturization.

Strict requirements to the reliability of device operation, safety of handling the device and preserving its properties during its warranted life made for particularly thorough development of the device structure.

In a Report on the Device-Related Progress dated October 18, 1947, N.N.Semenov, A.P.Aleksandrov and Ya.B.Zeldovich pointed out that there was a pavilion under construction for critical mass studies, and that no activities were conducted at KB to develop methods and study approaches to safe experiment conducting at that time.

The situation changed next year, and according to a record of discussion of the progress in identifying plutonium's nuclear constants and critical masses of January 5, 1949, G.N.Flerov reported that the critical mass would be identified using three techniques and that a test bed for critical mass measurements was under construction.

Engagement in 1946 of State Special Design Bureau 47 (GSKB-47) in choosing the outline of the atomic bomb's casing, its design and fabrication was of no use, even though this design bureau was our country's leader in the air bomb development. A casing developed by KB-11 itself in the same conventional manner failed during the flight tests, as well.

This was attributed to the lack of stability along the drop trajectory, i.e. swinging with inadmissibly high amplitudes, whereas such amplitudes were strictly limited, which had never earlier been demanded of "conventional" air bombs, if those satisfied the requirement of stability of their ballistic properties (common for conventional and for atomic bombs).

In parallel to the development of its own version, in choosing the outline KB-11 resorted to the help of TsAGI. Blowing-through in its wind tunnels of an enormously great number of outline modifications (over 100, under the direction of S.A.Khristianovich) started yielding fruit. The outline thus developed became standard and was a pattern for the outline of almost all atomic bombs of KB-11.

The necessity of using a complex automatic control system was another feature that fundamentally distinguished atomic air bombs from conventional ones.

The automatic control system consisted of safety stages and remote firing (take-up) sensors; starting, "critical" and contact pickups; energy sources (batteries) and triggering system (including a set of detonating cups) to ensure simultaneous of the latter ones with a microsecond-range diversity.

Thus, the 1949 tests were the tests of not only the atomic device, but also of the first Soviet bomb capable of military service:

- TU-4 was selected for bomb dropping;
- several air bomb designs were developed; their flight tests were conducted and outlines and designs meeting the requirements of atomic weapons were chosen;
- the bomb's automatic control system and the plane's control panel were developed to guarantee suspension, flight and atomic bomb dropping safety, detonatiing at a given altitude, and, along with this, plane's post-blast safety.

It is noteworthy that prior to the construction of the first atomic bomb, in 1948 there was set a task of carrying out investigations into feasibility of efficient defense systems to respond to atomic weapons. This proposal was put forward by N.N.Semenov, Head of the Institute of Chemical Physics of the Soviet Academy of Sciences. The main idea of the proposal was to study the effects of high-energy particle flows (neutrons, protons, deuterons) on the fissionable materials, outer layers of the atomic bomb and the atmosphere. The proposal provided for building special amplifiers to allow production of particles with the energies over 100 MeV. The first phase of the experimental work was to be accomplished using available facilities and natural background of cosmic rays. In August 1948 the Council of Ministers of the Soviet Union adopted a resolution, which charged the Institute of Chemical Physics, the Institute of Physics of the Soviet Academy of Sciences, Laboratory 2 and the Institute of Physics and Engineering of the Ukrainian Academy of Sciences with necessary research activities in this area in 1948-1949. This project was a forerunner of further developments of nuclear weapons defense systems.

1.3. Cooperation of KB-11 and Other Institutes

Through the initiative of B.L.Vannikov, M.G.Pervukhin, I.V.Kurchatov, A.P.Zavenyagin, Yu.B.Khariton and P.M.Zernov, the preparation project for the RDS-1 and RDS-2 development involved institutions discussed earlier by the Technical Board scientific, design and industrial and controlled by

- the Soviet Academy of Sciences;
- the Ministry of Agricultural Engineering;
- the Ministry of Transport Engineering;
- the Arms Ministry.

Later, this range of institutions and enterprises was supplemented with those of

- the Ministry of Communication Means Production;

- the Ministry of Electrical Industry;
- the Ministry of Aviation Industry;
- the Ministry of Nonferrous Metallurgy;
- the Ministry of Metallurgy Industry.

The Academy’s institutes included the Institute of Chemical Physics (IKhF), Steklov Institute of Mathematics and its Leningrad Branch, Institute of Geophysics, the Institute for Physical Problems, the Radium Institute (RIAN), the Physical and Technical Institute (FTI), the Physical institute (FIAN), the Institute of Physical Chemistry (IFKhI), the Institute of General Inorganic Chemistry (IONKh), Ural Branch of the Soviet Academy of Sciences, Vernadsky Biochemical Laboratory of the Soviet Academy of Sciences, the Institute of Physics and Engineering of the Ukrainian Academy of Sciences.

The Institute of Chemical Physics had been involved in the projects of the First Main Directorate since 1946 (some of its associates, for instance, Yu.B.Khariton – since 1943). This project was prioritized among the Institute’s research projects: about 80% of its total scientific and engineering manpower focused their efforts on it.

During phase 1 (1946 through 1949), IKhF dealt with sophisticated fundamental issues related to the theory of spherical detonation wave convergence in explosives and wave effects on a metal nucleus, to the equation-of-state studies as applied to structural materials, explosion efficiency studies and criticality calculations.

Jointly with KB-11 IKhF developed various recording methods for transients, provided methodical and hardware support for gas-dynamic investigations. Based on the general nuclear explosion theory developed by the Institute of Chemical Physics, there were identified major areas of experimental explosion studies and developed novel special instrumentation for measuring nuclear explosion parameters and destructive effects.

Associates of the Radium Institute headed by Academy Member V.G.Khlopin worked on the grand-scale plutonium production technology and radiochemical methods for radioactive isotope fission products extraction. They advanced and verified a technology for plutonium separation from dissolved irradiated nuclear reactor units by sodium diacetate and uranium or plutonium deposition.

This technology was tested on a pilot scale and improved by the All-Union Research Institute of Inorganic Materials headed by Z.V.Ershova and V.D.Nikol’sky. One of the leading specialists in radiochemistry was Corresponding Member of the Soviet Academy of Sciences A.N.Nikitin.

The first uranium studies were initiated in the Giredmed, and in 1946 transferred to the All-Union Research Institute of Inorganic Materials, where under the direction of A.N.Vol’sky and F.G.Reshetnikov was developed and mastered reduction metal smelting.

In 1947, at the All-Union Research Institute of Inorganic Materials there was established a department for plutonium metallurgy (directed by A.A.Bochvar). In the metallurgy laboratory headed by A.N.Vol’sky there were created teams for reduction (F.G.Reshetnikov) and refining (Ya.M.Sterlin) plutonium smelting. Early in 1948 the group of Ya.M.Sterlin produced the first batch of plutonium. This proved the technology to be adequate and allowed development of production facilities.

One should note that most of calculations of that time were performed at four special mathematical divisions:

- the division for approximate calculations of Steklov Institute of Mathematics of the Soviet Academy of Sciences headed by K.A.Semendyayev;
- the bureau of calculations of the Institute for Physical Problems headed by N.N.Meiman;
- the mathematical department of the Institute of Geophysics of the Soviet Academy of Sciences headed by Corresponding Academy Member A.N.Tikhonov;
- the division for approximate calculations of the Leningrad Branch of Steklov Institute of Mathematics headed by Professor L.V.Kantorovich.

Bomb parts were also developed by attracted institutions. There were issued individual task orders, but not all of such institutions managed to meet strict requirements. Therefore, KB-11 carried on parallel activities.

This work manner gave rise to the multidisciplinary approach of KB-11.

1.4. The First Atomic Bomb

These were the main structural components of the first atomic bomb:

- nuclear warhead;
- detonation device and automated warhead ignition system with safety systems;
- ballistic casing of the air bomb, in which were located the nuclear warhead and the automated ignition system.

The basic principles that determined the RDS-1 design were attributed to

- the decision to ensure maximum preservation of the basic scheme of the U.S. atomic bomb tested in 1945;

- the necessity of assembling the warhead located inside the bomb’s ballistic casing at the testing ground immediately before the explosion for safety reasons;
- the possibility of RDS-1 bomb dropping from TU-4 heavy bomber.

The RDS-1’s atomic warhead was a layer-cake-type structure, in which the active material, plutonium, was made supercritical by compression with a converging spherical detonation wave in HE.

The plutonium core consisting of two hemispheres was located in the center of the nuclear warhead. Final decision on the mass of plutonium was made in July 1949.

Inside the plutonium core in a composite shell of natural uranium there was mounted a neutron initiator. During 1947-1948 there were considered about 20 different proposals regarding neutron initiator operation, design and optimization principles.

One of the most complex parts of the first atomic bomb, RDS-1, was the HE charge of TNT alloyed with cyclonite.

The choice of the outer diameter of the HE charge was determined by the necessity of gaining a satisfactory energy yield on the one hand and by admissible outer dimensions of the device and engineering production capacities on the other.

The first atomic bomb was developed in view of its being suspended in the TU-4 plane, whose bomb hatch allowed for a device with an up to 1,500-mm diameter. The middle of the RDS-1’s ballistic casing was determined based on this very dimension. The HE charge was a sphere consisting of two layers.

The internal layer was assembled of two hemispheres made of domestic TNT-cyclonite alloy.

The outer layer of the HE charge of the RDS-1 was assembled of individual parts. This layer that produced a spherical converging detonation wave in HE and was called “lens system” was one of the basic functional parts of the device, which in many respects determined its tactical and technical performance.

The main purpose of the bomb’s automated control system was to produce an explosion at a predetermined trajectory point. Part of the bomb’s electric equipment was located aboard the bomber, and some of its components were mounted at the nuclear warhead.

In order to enhance operational reliability of the device, as applied to some automated firing tools there was used a two-channel (duplicating) scheme. Should the high-altitude detonator fail, the bomb was equipped with a special device (shock sensor) to produce a nuclear explosion on impact of the bomb striking against the ground.

As early as at the initial stage of the nuclear weapons development it became evident that studies of the in-warhead processes should be based on the computational and experimental approach enabling revision of theoretical analysis taking into account experimental data of the gas-dynamic properties of nuclear warheads.

Optimization of the nuclear warhead in terms of gas dynamics implied a number of investigations relevant to experimental setups and recording of transients including shock wave propagation in heterogeneous environments. The studies of materials properties at the gas-dynamic stage of nuclear warhead's operation, when the range of pressures reached tens of millions of atmospheres, necessitated the development of fundamentally new approaches, including new methods for transients recording. The Research Department of KB-11 laid the foundation for the domestic high-speed streak-camera imaging with an up to 10-km/sec scanning rate and a frame rate of about 1 million frames per second.

Of principal importance for computational and theoretical serviceability verification of the first device were the parameters of explosion products (EP) behind the detonation front and dynamics of spherically symmetric compression of the central part of the device. To study these, in 1948 E.K.Zavoisky proposed and developed an electromagnetic method for recording mass velocity of explosion products behind the detonation front applicable for both plane and spherical explosions.

Explosion products' velocity distribution was studied in parallel using the pulsed-radiography method by V.A.Tsukerman.

The new methods and advanced recording devices enabled KB-11 to obtain necessary data on the dynamic compressibility of structural materials as early as at the outset of the atomic weapons project.

Experimental studies of the constants of working substances, which belonged to the warhead's physical scheme, laid the foundation for verifying physical concepts as to the processes running inside the warhead at the gas-dynamic stage of its operation.

On the whole, the studies of materials compressibility under dynamic loads resulted in the formation at VNIIEF of a world-wide-known scientific school of physics of high pulsed pressures.

Of fundamental importance were adequate understanding and specific measurements of processes that took place at spherical HE implosion, and development of appropriate structural parts and technology for their fabrication. As a result, in a short period there was developed a practically new technology for high-precision HE-containing large-size structure designing.

Let us point out that the first studies of transients associated with detonation propagation at HE ignition were carried out as early as 1948 by E.P.Feoktistova.

Of great value was a proposal of V.M.Nekrutkin that allowed considerable reduction of the warhead's size owing to a new system for converging detonation wave production.

Applied gas-dynamic studies were directed toward the development and experimental verification of actual nuclear warhead designs. The experiments involving simulators and mock-ups reproduced all operational stages of the warhead starting with the initiating systems development and HE ignition and extending to the pulsed-radiographic recording of actual compression of a fuel imitator.

In 1947 Alexander Sergeyevich Kozyrev formulated a concept of a thermonuclear fusion reaction at spherical implosion by compressing a tiny amount of thermonuclear fuel. Historically, this proposal was the first step towards the inertial confinement fusion.

1.5. Preparation of the Testing Ground for Testing of RDS-1

The place for the testing ground was chosen in the region of Semipalatinsk, Kazakhh Republic in an arid partly hilly steppe with a few derelict dried-up wells and salt lakes.

The site intended for building the testing installation was a flat with a ~20-km diameter surrounded with hills in the south, west and north.

The headquarters of the military division responsible for the preparations of the testing ground for the tests and residential district with scientific and material facilities were located on the shore of the Irtysh River 60 km northeast of the testing ground and 120 km of Semipalatinsk.

Construction of the testing ground was initiated in 1947 and completed towards July 1949. These two years saw a tremendous amount of effort of high quality and high engineering level. All materials were delivered to the construction sites located at a distance of 100-200 km by trucks moving along unpaved roads. Traffic continued around the clock both in winter and in summer.

For the atomic bomb tests the testing ground was made such as to include

- a testing site with a 10-km radius with special structures for testing, monitoring and physical measurements;
- site "N" with buildings and structures for putting-together the bomb before the tests and storing parts of the atomic bomb, instruments and equipment;
- site "Sh" to accommodate the headquarters and power facilities of the testing site.

The testing site included numerous constructions with instrumentation and military, civil and industrial objects to study destructive effects of a nuclear explosion.

There was a 37.7-m-high metal tower in the center of the testing site, atop which was to be placed the RDS-1.

The testing site was divided in 14 testing segments: two fortification segments, one segment with civil constructions, a physical segment, military segments to accommodate military vehicles and a biological segment.

Northeast and southeast along the radii at different distances from the center there were constructed instrumentation buildings to place streak cameras, movie cameras and oscilloscopes to record explosion processes.

At a 1,000-m distance from the center there was built an underground structure to lodge equipment that recorded light, neutron and gamma rays produced by the nuclear explosion.

The optical instruments and oscilloscopes were wired to a programmed control panel.

For studying the nuclear explosion effects, at the testing site there were constructed sections of subway tunnels and airstrips and placed airplane, tank and artillery rocket launcher models and watercraft structures of different types. 90 railcars were used to bring these military objects to the site.

44 structures were built and a 560-km-long cable network was laid at the testing site to ensure operation of the physical segment.

1.6. RDS-1 Test

On July 27, 1949, a governmental commission for the RDS-1 tests headed by M.G.Pervukhin started its activities. On August 5 the commission declared the testing ground to be completely prepared and suggested that during 15 days there should be conducted a thorough run-through to practice all bomb assembly and detonation operations. The tests were scheduled for late August.

I.V.Kurchatov was appointed Scientific Leader of the tests, Major-General V.A.Bolyatko directed the preparations of the testing site for the tests on behalf of the Defense Ministry, M.A.Sadovsky was Scientific Leader of the testing ground.

During the period from August 10 to 26 there were performed ten run-throughs to practice testing ground management and warhead detonation equipment control, as well as four exercises involving operation of all instruments and 4 blasts of actual HE charges in aluminum spheres using the automatic ignition system.

The exercises proved the warhead assembly to be of high quality, the automatic ignition system and detonation line to be reliable and of all services and personnel to be ready for actual tests.

After the main explosion run-through, the control system was entrusted to K.I.Shchelkin who was responsible for it until the nuclear tests began.

On August 21, a special train brought the plutonium warhead and four neutron initiators, one of which was to be used to trigger the device, to the testing ground.

Pursuant to a directive of L.P.Beria, Scientific Leader of the tests I.V.Kurchatov gave an order to detonate the RDS-1 at 8 a.m. local time on August 29.

On the night of August 29, 1949 the bomb was finally put together.

The core including the plutonium parts and the neutron initiator was assembled by a team including N.L.Dukhov, N.A.Terletsky, D.A.Fishman and V.A.Davidenko.

Final assembly of the device headed by A.Ya.Mal'sky and V.I.Alferov was completed by 3 a.m. on August 29. Members of the Special Committee L.P.Beria, M.G.Pervukhin and V.A.Makhnev supervised the final operations.

By 6 a.m. the device was put at the top of the testing tower, the detonators were mounted and the device was wired to the ignition system.

In view of the bad weather, all approved activities were conducted an hour ahead of schedule.

At 6.35 a.m., operators supplied power to the automatic system, and the automatic system of the testing ground was switched on at 6.48 a.m.

At 7 a.m. sharp on August 1949, the entire area was illuminated with a glare of light, which marked successful completion by the USSR of the development and tests of the first atomic bomb.

L.P.Beria heartily congratulated everybody on the successful tests and gave kisses to I.V.Kurchatov and Yu.B.Khariton. However, he probably still had some doubts about full completion of the explosion, because instead of making a call and reporting to I.V.Stalin on successful tests he moved to the second observation point to nuclear physicist M.G.Meshcheryakov, who had attended the U.S. atomic demonstrations at Bikini Atoll in 1946.

There he also sincerely congratulated M.G.Meshcheryakov, Ya.B.Zeldovich, N.L.Dukhov and others. Thereafter, he asked M.G.Meshcheryakov about every detail of visible effects of the U.S. explosions. M.G.Meshcheryakov assured him that in this respect our explosion surpassed the U.S. ones.

Having got a confirmation from the witness, L.P.Beria went to the testing ground headquarters to report to I.V.Stalin on the successful testing.

Twenty minutes after the explosion, two lead-protected tanks were sent towards the site center for radiation monitoring and site center examination.

All the structures in the field center were found to be demolished. There was a crater instead of the tower; soil in the field center fused and there was a total-surface scoria crust. Civil constructions were destroyed or damaged.

The instruments used during the tests enabled optical observations and measurements of the heat wave, shock wave parameters and characteristics of neutron and gamma radiation, estimation of radioactive contamination in the explosion region and along the cloud path, studying the nuclear explosion’s destructive effects on the biological objects.

The energy release of the first Soviet atomic bomb was equivalent to 22 kilotons of TNT.

1.7. Results of the RDS-1 Testing

The heads of the first Soviet atomic bomb project from politics, military industry and science were satisfied with the results of the tests.

The development and successful tests of the first Soviet atomic bomb were accomplished.

Direct experimental data were obtained on the enormous aftermath of the nuclear explosion produced by the developed device as applied to the parts of military vehicles and industrial structures. There was created an experiential foundation for taking into account nuclear weapons’ capabilities in military operations.

The concepts on the features of nuclear warhead operation were verified and opportunities for further nuclear weapons improvement were offered.

The data underlying the Soviet atomic project were proved to be correct.

The Soviet Union became holder of the nuclear weapons technology and succeeded in establishing its production.

The basic purpose of the tests was to experimentally verify the nuclear weapons development technology chosen. Particular attention was paid to the check of a copy of the U.S. atomic bomb. Such an approach enabled

- minimization of failure risk during the first experiment (which was of extra importance under the conditions of the U.S. nuclear monopoly);
- technology verification and building the atomic device to become a starting point for nuclear weapons optimization;
- experimental studies of capabilities of a nuclear explosion in view of its being a blast produced by a typical U.S. nuclear device;
- experimental quality control as applied to the key materials and parts necessary for nuclear weapons development.

One cannot but point to the importance of the fact that in spite of the likeness of the warhead’s scheme to the U.S. one, its design, production and technology were of the Soviet origin.

A small batch of five RDS-1 atomic devices was deployed in Arzamas-16 in 1950. It was a special reserve to be resorted to in case of extra-emergency.

The history of the first Soviet atomic bomb development is an example of high order exhibited by all services having diverse duties, self-denial of all project participants, efficient interaction and high responsibility in fulfilling the task entrusted.

This period saw the formation of the working manner of the entire team involving researchers, designers, technologists, production and administration officers, which in spite of strict secrecy-related limitations demonstrated reliable and efficient interaction where possible of all divisions along with comprehension of significance and importance of performing the duties of each individual division.

The outcome of the Soviet atomic project was creation in 1949 of the first Soviet atomic device and its successful tests on August 29, 1949. The gap between the Soviet Union and the United States as to the nuclear weapons development made only 4 years. The U.S. President Garry Truman "could not believe 'those asiatics' could build so complicated a weapon as an atomic bomb" (Richard Rhodes, *Dark Sun*), and as lately as on September 23, 1945 he informed the U.S. public that the Soviet Union had tested its atomic bomb.

In their book called *To Win a Nuclear War: The Pentagon's Secret War Plans* (1987) and based on unclassified documents of the U.S. government M. Kaku and D. Axelrod wrote that as early as June 1945 after the Potsdam Conference the Joint Chiefs of Staff drafted a plan of an atomic war against the Soviet Union given the code name of Pincher. This plan provided for an assault involving 50 atomic bombs to destroy 20 cities. This plan was followed by other plans, such as

Plan 2, Broiler, issued in March 1948, which provided for dropping 34 atomic bombs on 24 Soviet cities;

Plan 4, Trojan, issued in January 1949, which provided for dropping 133 nuclear bombs on 70 cities (Russia at that time had neither bombs, nor warheads).

On August 29, 1949, Russia performed the first nuclear tests, which were responded in 1949 by Plan 6 called Dropshot, which provided for dropping 300 nuclear air bombs on 200 cities of the Soviet Union.

The increasing number of bombs to be dropped on the Soviet Union according to the Pentagon's plans was explained by the accelerated stockpile growing.

According to the experts, the total number of nuclear assault plans against Russia was 18. Knowing this, one could easily understand the urgency of nuclear weapons development and optimization for Russia.

2. Development of the Early Soviet Nuclear Weapons

2.1. RDS-2 and RDS-3 Atomic Bombs

As early as at the stage of the development of the first Soviet atomic bomb RDS-1, which was based on the U.S. atomic bomb scheme, the scientists became aware of the drawbacks of its conceptual design.

The spherical HE charge of the RDS-1 was surrounded with a lens system of chunks simultaneously fired by detonators and transforming diverging detonation waves from the detonators into one spherically converging detonation wave.

The operation of the lens system was based on the difference in detonation velocities of its individual components. Its design was such that it took the detonation the same time to make its way from the firing point to any point on its internal spherical surface irrespective of the way. As the system's components there were used two types of high explosives with different detonation rates.

A considerable drawback of the RDS-1's lens system was its thickness and, consequently, great mass of the HE blocks which made about 67% of the total HE mass. This was attributed to the small detonation rate difference between the high explosives used in the lens system.

After the tests of the first atomic bomb RDS-1, developers' efforts were focused on the improvement of the warhead's design and performance. Optimization of the implosion principle was directed towards warhead mass reduction and power enhancement. Outstanding contributions to the development of the implosion concept and its implementation were made by L.V.Al'tshuler, Ye.I.Zababakhin, Ya.B.Zeldovich and K.K.Krupnikov.

The next atomic tests after the RDS-1 explosion took place as lately as in the second half of 1951. There were developed atomic devices called RDS-2 and RDS-3 (they differed only in the composition of their nuclear core). As mentioned above, the decision on making the improved atomic bomb designs was made by the Council of Ministers of the Soviet Union in 1948 and confirmed after the RDS-1 tests. This decision and the shape of the first RDS modifications were apparently in some respect influenced by data passed along by Klaus Fuchs in 1948 in London. One of the main dimensions of the RDS-1, namely the outer diameter of the main spherical HE charge, and the HE composition, a 1:1 mixture of – TNT-cyclonite 50/50, in the RDS-2 and RDS-3 were left unchanged.

Gas-dynamic studies and tests with explosive elements were conducted by scientific and experimental teams headed by V.K.Bobolev, A.D.Zakharenkov and G.A.Tsyrkov. One of the principal tasks of those studies was to establish optimal parameters (radius, mass, thickness) of the warhead layers. Respective numerical modeling was carried out at Steklov Institute of Mathematics of the Soviet Academy of Sciences under the direction of K.A.Semendyayev.

The lens system of the RDS-2 and RDS-3 fundamentally differed from that of the RDS-1. It was made such as to exclude the drawback attributed to the operation principle of the lens system resting upon the difference in the HE detonation velocities. This allowed considerable reduction of the height and mass of the focusing belt.

Similarly to the RDS-1, the design of the RDS-2 and RDS-3 atomic devices provided for the final putting-together including insertion of the parts containing fissile materials through a hole in the warhead using special mounting tools and a special inspection tool. This operation was conducted at the testing ground immediately before the explosion of the devices.

The design of the insertion channel was as follows: in the spherical HE charge there was a through cone-shaped hole, which in the ready-to-service state was sealed with a suitable cone-shaped HE plug. The outer housing of the device, which enveloped the HE charge, the lens system and the array of inside shells of the central part, was provided with appropriate hatches located along the axis of the HE plug and sealed by means of plug-type connections with covers or plugs of the same thickness and material as the shells themselves. The final assembly procedure provided for sequential mounting and appropriate control of the nuclear core and parts of the insertion channel.

The RDS-2 and RDS-3 were successfully tested on September 24 and October 18, 1951, respectively. As compared to the RDS-1, they had smaller diameters and masses and about a twice-as-high yield. The chain reaction was set off by a neutron initiator similar to that of the RDS-1, which was located in the center of the nuclear device and emitted neutrons when affected by the shock wave.

One of the key questions, which occurred in view of the field testing, was how to test the devices – atop a tower, like the RDS-1 or by dropping them from a plane.

A scientific and technical panel devoted to the tests at the Semipalatinsk testing ground revealed disagreement on this subject. Warhead developers headed by Yu.B.Khariton considered it necessary to conduct the tests atop of the tower (similarly to the RDS-1) in order to more accurately identify its yield and obtain more reliable data on the chain reaction development.

Leaders of the atomic project headed by I.V.Kurchatov supported the idea of flight tests by dropping the bomb from a plane on a target. In this case, along with identifying the yield, the Soviet Union could conduct the first tests of a warlike atomic bomb.

The final decision-making was delegated to the First Main Directorate, which resolved to conduct the first military tests by dropping the bomb from TU-4. However, in the course of further discussions there was made a “decision worthy of Solomon” – the RDS-2 with plutonium core was to be tested atop of the tower and the RDS-3 with combined core was to be dropped. And so they did: RDS-2 was exploded at the top of a 30-m-high tower (E = 38 kt) and RDS-3 was dropped on a target from the altitude of 400 m above the ground (E = 42 kt). Thus, on October 18, 1951, the Soviet Union for the first time tested its atomic bomb by dropping it on a target.

The fundamental features that distinguished the RDS-2 and RDS-3 from the RDS-1 formed the basis of the scheme and design of domestic nuclear weapons. The RDS-2 and RDS-3 were introduced into large-scale production.

2.2. Atomic Warheads for Early Tactical Nuclear Weapons

The RDS-2 and RDS-3 nuclear devices were developed for air bombs to be dropped from heavy bomb carriers. Further air bomb improvement plans were focused on the bomb size and mass minimization, so that such bombs can be dropped from IL-28 medium-size jet bombers stationed at the airdromes of the European warfare theater.

In its size, mass and suspension parts such an atomic bomb was to be similar to a HE bomb. The conceptual design of a new device called the RDS-4 was based on the expertise gained during the RDS-2 and RDS-3 projects. The parts of the bomb were named starting with the letter “T” for “tactical”.

The RDS-4 used the nuclear core and the neutron source of the RDS-2. As HE was also used the 50/50 TNT-cyclonite mixture, however, in a notably smaller amount.

The RDS-4 was successfully tested on August 23, 1953 at the Semipalatinsk testing ground by dropping from a plane. The bomb was suspended beneath the IL-28 plane, which, escorted by a dubbing plane and two MIG-17 fighters, climbed to 11,000 meters and on leveling off dropped the bomb down to an objective. The bomb exploded 600 meter above the ground. The plane flying with a 660-km/h speed was caught in the first shock wave followed by the second and the strongest and finally the third and the weakest one.

Later, the RDS-4’s warhead was used as combat equipment for the surface-to-surface ballistic midrange liquid-fueled R-5M missiles.

The development of the R-5M was initiated at Special Design Bureau 1 headed by Chief Designer S.P.Korolev. 1951 saw a resolution issued by the Council of Ministers of the Soviet Union on setting up a large-scale production of the R-5M at

State Factory 586 (later called Southern Machine Building Works) established on the basis of the Dnepropetrovsk Motor Works. Flight tests of the R-5M were started on January 20, 1955. In 1954, there was established a separate design bureau of Factory 586, Special Design Bureau 586 (Southern Design Bureau), Chief Designer of which was M.K.Yangel. Later, this bureau became leader in the development of ballistic missiles for strategic rocket forces.

1953 and 1954 were devoted to experimental and theoretical studies aimed at the reduction of the mass of deficient plutonium in warheads. At that time there was no sufficient amount of fissile materials to completely meet respective demand. As early as 1949 when the development of the first atomic bomb was underway, I.V.Stalin, listening to the reports of the RDS-1 pre-testing preparation project leaders asked Yu.B.Khariton, whether it was possible to build two lower-yield bombs instead of one using the same amount of plutonium in order to have one bomb in reserve. Bearing in mind that the stock of plutonium produced by that time was just the amount to make a warhead according to the U.S. scheme, and that needless risk was inadmissible, Yu.B.Khariton replied negatively. One cannot exclude the possibility that this episode influenced further project evolution focused on the minimization of plutonium amount in warheads and studies of other physical effects entailed by this. The 1953-1954 field tests yielded important data in terms of further investigations, plutonium mass optimization and implosion-based warheads’ yield enhancement. The results of these field tests formed the basis for the development of a modification of the RDS-4 atomic bomb, named RDS-4M, with a smaller-mass and, consequently, lower-yield nuclear core. This warhead was mounted in the bomb having the same name, as well as in the nose cones of the R-5M ballistic missile and cruise missile launched from a mobile launcher (earlier called projectile-airplane).

1953-1954 saw the outset of atomic warhead development for the T-5 torpedo. The torpedo had a standard 533-mm caliber. There was a need to considerably reduce the warhead diameter as compared to the previous warheads of the RDS-4 family.

The design-related solution to the problem consisted in the reduction of the radius and, consequently, mass of HE, which resulted in the decrease of the warhead’s yield. On the other hand, this necessitated fundamental modification of the nuclear warhead design which allowed minimize the spacing between the warhead casing and the inside cylindrical surface of the warhead-carrying compartment of the torpedo. As compared to the earlier developed RDS-family warheads, the conceptual approach to the warhead design remained unchained; however, its HE had much higher capacity and a proportion other than TNT-cyclonite 50/50.

Theoretical warhead-related issues were studied by Ye.I.Zababakhin, M.K.Nechayev, design aspects were addressed by a team headed by

V.F.Grechishnikov, and gas dynamic studies were conducted under the general leadership of V.K.Bobolev.

The warhead underwent the entire scope of gas-dynamic and design verification and was approved for field tests.

The tests started on October 19, 1954 at the Semipalatinsk testing ground and failed: no explosion took place. This was the first failure in the nuclear warhead development history. For the purposes of these first tests of the torpedo atomic warhead, there was erected a 15-m tower surrounded with measuring equipment and standard and pilot structures to study destructive effects of the blast.

At the moment of explosion, there was observed a small cloud at the point of tested warhead location, which was immediately cleared away by the wind. There were detected no manifestations typical of atomic explosions. The check of the instruments revealed the signals for instrument triggering to be normal. Follow-up α-activity measurements of the soil demonstrated that the tower was located in one of the foci of an ellipse extended along the wind direction. From this followed, that the nuclear core was dispersed and the area was radioactively contaminated.

Minister for Medium Machine Building V.A.Malyshev by his degree established a special commission to investigate failure reasons and named I.V.Kurchatov its chairman. The conclusion of the commission was that at that time it did not seem possible to adequately establish the reason why the atomic explosion had failed.

There were given a number of versions of the failure reasons. These versions formed the basis for further laboratory experiments. The studies were conducted but again provided no unambiguous explanations to the failure. The outcome of the studies that could facilitate making warhead operation more reliable in general was used at the development of next warhead modifications.

For the 1955 tests there were prepared several modifications of torpedo warheads, which differed in design, amount of used fissile materials and nuclear initiation principle. In the new modifications the central part and new compressing HE charge were kept separately.

During July-August 1955 at the Semipalatinsk testing ground there were conducted three successful atomic explosions, which made it possible to select the most efficient warhead design for the T-5 torpedo. Two of them were used to compare the efficiency of internal and external initiation systems.

This experimental comparison demonstrated the advantages of the external pulsed neutron source producing a neutron pulse at a proper moment. Thenceforth the development, improvement and utilization of the external pulsed neutron source as the most efficient chain reaction initiation tool was considerably livened up.

This warhead carried by the T-5 torpedo was tested by an underwater (at a 12-m depth) atomic explosion at the Northern test site on September 29, 1955. Its yield was 3.5 kt.

The T-5 tests were the first atomic explosion conducted at the Northern test site. These tests took place, since it was necessary to study the effects of an underwater explosion on Navy objects and develop a theory of underground applications of atomic weapons. By that time the United States had already conducted underwater nuclear explosions in the region of Bikini Atoll and in the waters of the Pacific Ocean.

During the tests, Navy vessels located at various distances from the detonated torpedo were damaged to different extent; having its hull seriously damaged in the central part, the Reut destroyer located at a 250-m from the explosion center sank.

2.3. Development of Devices to Enhance the Efficiency of Atomic Weapons

As a chain-reaction initiator the early RDS-2, RDS-3 and RDS-4 warheads used the so-called neutron initiator (NZ), placed in the center of the atomic core and producing neutrons when impacted by a shock wave. There was a significant drawback about it: shock wave caused neutron emission at an improper moment, as a rule, earlier than maximum compression of the nuclear core could be achieved, which reduced the efficiency of the chain reaction.

The second generation of neutron initiators was represented by a neutron source (NI). Similarly, it was mounted in the center of the nuclear core and, as distinct from the NZ, had an unvaried neutron background pre-calculated based on the specific parameters of a warhead. The NI appeared due to the development of a new design of the nuclear core. The NI was first used in the RDS-4-type warhead tested in 1953. Similar to the RDS-1’s neutron initiator, it started the chain reaction prior to the maximum compression of the nuclear core. The basic drawbacks of the neutron source included yield instability, lack of safety attributed to the constant presence of the neutron background and short operational life because of the decay of its working medium. Therefore it was not introduced into large-scale production.

The search for a way to produce a neutron pulse at the maximum-compression moment became urgent.

As early as 1948 Ya.B.Zeldovich and V.A.Tsukerman put forward a concept of external neutron initiation. The transition to the external neutron initiation enabled to ensure the optimum neutron initiation. Feasibility of such external neutron source was repeatedly discussed in 1948-1949 together with specialists in the area of acceleration and high-voltage equipment.

It became evident soon that it was impossible to make a neutron source with acceptable dimensions and weight using high-voltage components and technologies available at that time.

3. Development of Early Thermonuclear Weapons

3.1. Initial Data

The Soviet thermonuclear weapons development project was an important component of an unprecedented in scope and postwar-time-related difficulties struggle centered on breaking the U.S. monopoly in possessing nuclear weapons and attaining nuclear parity with the United States.

This effort was initiated in 1945, when the Soviet Union learnt about the U.S. super-bomb project. Information on the U.S. super-bomb project was first provided to the Soviet Union by several sources via the Intelligence in the second half of 1945.

One of these sources was Klaus Fuchs, associate of the Los Alamos National Laboratory's Theoretical Division and member of the British legation in Los Alamos. He passed along documents to the Soviet Union via U.S. citizen Harry Gold. The documents contained specific data on the development of a deuterium super-bomb, as it was projected in the middle of 1945. Upon his return to England Klaus Fuchs resumed his communication with the Soviet Intelligence and between fall 1947 and May 1949 six times submitted written data to the Soviet Union via A.S.Feklisov, Soviet Intelligence officer. These data, namely, included a conceptual design of a hydrogen bomb and theory of its development advanced by American and English scientists by 1948.

The data received in 1945 on the U.S. super-bomb project could not but excite political and scientific heads of the Soviet atomic project. The super-bomb issue was included by I.V.Kurchatov in a list of questions to be addressed to Niels Bohr, who returned from the United States to Denmark, by Officer of Bureau 2 of the Special Committee of Sovnarkom Ya.P.Terletsky responsible for atomic bomb-related intelligence processing during their meeting at Copenhagen on November 14 and 16, 1945.

In parallel to arranging the meeting with Niels Bohr, when the above documents were under study in Bureau 2 (they contained not only information regarding the U.S. super-bomb project but also novel atomic bomb-related data), I.V.Kurchatov must have addressed a group of the leading Soviet physicists including detonation theorists I.I.Gurevich, Ya.B.Zeldovich, I.Ya.Pomeranchuk and

Yu.B.Khariton. He probably explained them how the task had been formulated, familiarized them with some initial data, and then proposed studying the feasibility of nuclear detonation in a deuterium cylinder driven by an atomic bomb explosion (this super-bomb development direction was discussed in the documents provided by Klaus Fuchs).

3.2. Report of I.I.Gurevich, Ya.B.Zeldovich, I.Ya.Pomeranchuk and Yu.B.Khariton on Thermonuclear Detonation

I.I.Gurevich, Ya.B.Zeldovich, I.Ya.Pomeranchuk and Yu.B.Khariton prepared a report entitled "Utilization of Nuclear Energy of Light Elements", which was presented at the 12th Meeting of the Technical Board of the Special Committee of the Council of People's Commissars on December 17, 1945. The above meeting gathered Technical Board members B.L.Vannikov, A.I.Alikhanov, I.N.Voznesensky, A.F.Ioffe, P.L.Kapitza, I.K.Kikoin, I.V.Kurchatov, V.A.Makhnev, Yu.B.Khariton, V.G.Khlopin and Special Committee member M.G.Pervukhin. All the authors of this report were then invited to listen to, and to participate in the discussion of the second agenda item, "On Possibility to Initiate the Reactions in Light Nuclei", a presentation made by Ya.B.Zeldovich. The report "Utilization of Nuclear Energy of Light Elements" pointed out the advisability of extending range of elements, whose nuclear reaction might be of practical value for energy production or explosions. All the practical applications of nuclear reactions known before that moment were based on nuclear fission. Nuclear fission was typical only of uranium, thorium and new uranium and thorium derivative elements. The energy of nuclear reactions in light elements, when normalized to unit weigh, in most cases was higher than that of high elements' nuclear fission. A nuclear reaction in the light-element media, however, could run without decay only at rather high temperatures of the entire body of a material. The energy of the nuclear reaction distributed between all system's nuclei and electrons achieved for many light-nuclei reactions 1 to 2 MeV. This energy was sufficient to start a fast nuclear reaction. However, part of the energy at absolute thermal equilibrium converted into radiation. This phenomenon did not allow the equilibrium mean energy of charged particles to go beyond the limit of 5 to 15 keV, which was too low for nuclear reaction initiation. The basic conditions to be satisfied for the fast light-nuclei reaction to get real included attaining the non-equilibrium distribution, at which, if possible, the entire energy would be concentrated in the charged particles as their kinetic energy, minimizing the energy fraction converted into radiation, and implementation of a detonation-type reaction. According to the report, the concept of this condition was that there was a shock wave that propagated along the reacting substance with a warming-up energy of the same magnitude as the reaction energy. Shock warming-up took a rather small amount of time of the order of charged particles' time of flight. Following this, the substance reacted, liberated energy and expanded pushing the shock wave in front of itself. The process made it feasible in principle to detonate an unlimited amount of a reaction-suitable light element by means of a predetermined sufficiently powerful initial pulse.

The report contained, according to its wording, a specific proposal. As pointed out therein, the system to meet the requirements specified was deuterium. "Detonation of deuterium involves the following reactions:

$$D + D = H + T + 4\ \text{MeV},$$

$$D + D = H + He^{3} + 3.2\ \text{MeV}.$$

Of particular value is the fact that owing to the low charge of nuclei, high reaction cross-sections are achieved already at a low energy ($5 \cdot 10^{-26}$ cm^{2} for each reaction, at the energy of collision relatively to the gravity center of 200 keV). For the same reason, the kinetic energy-to-radiation conversion is rather low and at a ~ 200-keV mean energy makes about one-fifth of the energy liberated by the nuclear reaction. According to the data available on the correlation between the reaction cross-section and particles energy, the minimum diameter a long deuterium warhead can be less than 30 cm. It is desirable for the deuterium density to be as high as possible, which can be achieved by using deuterium under high pressure.

In order to start the nuclear detonation it would be helpful to use heavy shells to slow down the spread.

The most challenging task is to initiate a warhead, since detonation in uranium, as well as in plutonium, develops comparatively slowly and, consequently, a considerable fraction of energy has enough time to convert into radiation, as a result of which the temperature and pressure of nuclei and electrons prove to be relatively low.

For the time being, unclear is how radiation affects uranium expansion, which imparts pressure to deuterium. It seems possible that in order to optimize the initiation one should use greater-size and shaped uranium charges and inject heavy elements into deuterium close to the initiator to respond to the radiation pulse.

Despite the remaining uncertainties about the initiation, it seems rather important that there has been discovered a system, in which one high-power pulse initiates a nuclear reaction of an unlimited amount of substance".

Of historical interest is the Technical Board's resolution regarding this report, which was the first official resolution associated with the Soviet hydrogen bomb project:

“1. Consider it necessary to conduct systematic measurements of cross-section efficiency in light elements’ nuclei using for this purpose a high-voltage electrostatic generator developed at the Kharkiv Institute of Physics and Engineering.

2. Entrust professor Ya.B.Zeldovich with preparing within three days of a task order for light elements’ nuclear reaction studies to be considered by the Technical Board”.

Noticeable is the fact that the Technical Board’s resolution discussed only initial experimental data and contained no instructions as to arranging and conducting feasibility calculations and theoretical studies of the super-bomb. This was certainly because of the aspiration to concentrate the maximum effort on the atomic bomb development.

Bureau 2 first reported about the intelligence on the atomic bombs and the super-bomb at the 16th Meeting of the Technical Board on January 28, 1946. The report was made by Ya.P.Terletsky. The participants of the meeting were Technical Board members B.L.Vannikov, A.I.Alikhanov, A.P.Zavenyagin, I.K.Kikoin, I.V.Kurchatov, V.A.Makhnev and Yu.B.Khariton. This meeting was also attended by Special Committee officers L.P.Vasilevsky, A.I.Vasin, N.S.Sadykin and P.A.Sudoplatov. In compliance with the Technical Board’s resolution, the documents under discussion including those related to the super-bomb were forwarded to I.V.Kurchatov for using these in further studies. Yu.B.Khariton was charged with making a report at one of the nearest Technical Board meetings containing a detailed analysis of the data presented in the report of Bureau 2.

Yu.B.Khariton presented his report at the 18th Meeting of the Technical Board, which took place on February 11, 1946, was attended by A.I.Alikhanov, A.P.Zavenyagin, I.K.Kikoin, I.V.Kurchatov, V.A.Makhnev and M.G.Pervukhin, but was devoted only to the issues related to the development and calculations of the atomic bombs. Among others, the meeting adopted resolutions on the involvement in the atomic bomb yield calculations of theoretical physicists of the Moscow Institute for Physical Problems of the Soviet Academy of Science under the leadership of L.D.Landau and on establishing a team in charge of calculations provided with all necessary calculation equipment to support the activities of the theoretical team.

3.3. Report of Ya.B.Zeldovich, S.P.Diakov and A.S.Kompaneits on Thermonuclear Detonation

In June 1946, in the Moscow Institute of Chemical Physics a group including S.P.Diakov and A.S.Kompaneits under the leadership of Ya.B.Zeldovich started theoretical studies of possible uses of the light elements’ nuclear energy. The first results of the effort by this group were discussed at the 97th Meeting of the Scientific and Technical Board of the First Main Directorate of the Soviet Council of Ministers, which took place on November 3, 1947.

For this meeting, S.P.Diakov, Ya.B.Zeldovich and A.S.Kompaneits prepared a report called “On the Uses of Light Elements’ Intratomic Energy”. Another report, “On the New Heat Sources” related to the subject of the meeting was made by Ya.B.Zeldovich.

The concept of the approach to the problem discussed in the report of S.P.Diakov, Ya.B.Zeldovich and A.S.Kompaneits was similar to that discussed in the 1945 report of I.I.Gurevich, Ya.B.Zeldovich, I.Ya.Pomeranchuk and Yu.B.Khariton, namely, to find out, what conditions were required to enable nuclear detonation in the environment of light nuclei caused by a shock wave, when there was no thermal equilibrium between matter and radiation.

The conclusion drawn in the report and presentation was that it did not seem possible to make any certain conclusions about practical uses of the light elements’ nuclear energy without additional theoretical and experimental studies. In case of positive answer to the question regarding detonation feasibility, it was necessary to develop a theory of detonation initiation.

The resolution of the Scientific and Technical Board of the First Main Directorate dated November 3, 1947 pointed out the importance of the light elements’ nuclear energy studies for the nuclear physics advancement and for practical purposes, in case of their success. It was stated necessary to proceed with these efforts, and, first of all, to study the conditions, at which reactions in light elements could be driven using detonation initiated by an atomic explosion.

March 13, 1948 saw an event that played an exceptional role in the further progress of the Soviet thermonuclear bomb project and fundamentally affected its structure and scope. It was on that day that Klaus Fuchs met A.S.Feklisov in London for the second time and handed over documents that proved to be of top importance. Among these documents there was one providing new theoretical data related to the super-bomb. It contained a detailed description of the Classical Super project with a new initiation system. It was a two-stage device based on the radiation implosion principle. As a primary atomic bomb it used a U-235 gun-type bomb with a reflector of beryllium oxide. The second part was made of a liquid DT-mixture. Radiation within the initiation section was reflected by a heavy casing of a material opaque for radiation. The initiation section sided with a long cylindrical vessel filled with liquid deuterium. In the vessel heading deuterium was mixed with tritium. The document provided a description of the principle of operation of the initiation part and contained a number of graphs characterizing it.

It presented experimental and theoretical data justifying feasibility of the project. Experimental data included cross-sections of D+T and He^3+D reactions. Theoretical data confirmed the possibility of DT-mixture ignition in the secondary part of the initiation section. This document, however, similarly to the theoretical document of 1945 contained no theoretical proof of the possibility of nuclear burning initiation and propagation in a cylinder with liquid deuterium containing most of the thermonuclear fuel. Normal operation of the two-stage initiation section of the super-bomb implied ignition of deuterium mixed with tritium in the cylinder heading and propagation of nuclear burning along the major mass of deuterium. The information given in the document was likely to comply with data presented in a patent of Klaus Fuchs and John von Neumann of 1946. On April 20, 1948, leaders of the Soviet Ministry of State Security forwarded the translated version of the documents received from Klaus Fuchs on March 13, 1948 to I.V.Stalin, V.M.Molotov and L.P.Beria. Political leaders of the Soviet Union took the new intelligence related to the super-bomb and improved modifications of atomic bombs for a proof of possible considerable progress of the United States in this project and necessity of prompt actions to speed up the feasibility studies of such bombs in the Soviet Union and rendering these studies official.

On April 23, 1948 L.P.Beria charged B.L.Vannikov, I.V.Kurchatov and Yu,B,Khariton with a task to thoroughly analyze the documents and draft proposals as to the arrangement of necessary investigations and activities with regard to the new data. On May 5, 1948 Yu.B.Khariton, B.L.Vannikov and I.V.Kurchatov expressed their ideas as to the documents submitted by Klaus Fuchs.

3.4. Decision on the Hydrogen Bomb Project Commencement. Establishing a Group Headed by I.Ye.Tamm.

In compliance with a resolution of the Council of Ministers of the Soviet Union dated June 10, 1948, at the Physical Institute of the Soviet Academy of Science there was established a group for theoretical hydrogen bomb studies under the leadership of Corresponding Member of Academy I.Ye.Tamm. S.Z.Belen'ky was appointed deputy head of the group. This group included A.D.Sakharov and V.L.Ginsburg, who became its member later. Yu.A.Romanov, who became postgraduate of the Physical Institute in 1948, joined the group shortly after this.

The resolution also called for involvement into KB-11's calculations of the Moscow Institute of Mathematics and its Leningrad branch. As mentioned above, the Institute for Physical Problems in charge of the atomic bomb calculations had joined the project earlier.

At first, in compliance with a plan of work on the hydrogen bomb provided for by the resolution of the Council of Ministers, at the Institute of Chemical Physics Tamm's group got acquainted with, and verified the calculations made by Zeldovich's group.

In a few months after the group of I.Ye.Tamm joined the project (most likely, it was September 1948), A.D.Sakharov started evaluation of a possible approach to the problem of hydrogen bomb development implying atomic explosion-driven initiation of nuclear detonation in a heterogeneous system, in which thermonuclear fuel alternated with uranium-238. This approach rested on the following idea: at temperatures as high as tens of millions of degrees typical of a nuclear explosion, equalization of thermonuclear fuel and uranium pressures at matter ionization allowed thermonuclear fuel layers located between uranium layers to gain in density, which considerably increased the rate of thermonuclear reactions.

The process of thermonuclear fuel densification in a layer-cake structure heated up to high temperatures was called by physicists, who closely worked with A.D.Sakharov, "sakharization".

Since that time, the Soviet hydrogen bomb project has been implemented in two directions. The group headed by Ya.B.Zeldovich, as before, studied the feasibility of nuclear detonation in deuterium, and the group of I.Ye.Tamm initiated studies of layer-cake structures of uranium and thermonuclear fuel.

Conceptual approaches to the problem of Ya.B.Zeldovich's team remained unchanged, as thermonuclear fuel, however, they started to consider liquid deuterium (in part mixed with tritium) contained in a cylindrical vessel. After June 1948, KB-11 also started studies of nuclear detonation feasibility in a cylinder with liquid deuterium.

Cylindrical deuterium-filled system studies were pursued at KB-11 through 1954, until they were finally and officially recognized as having no prospects.

At the first stage of his layer-cake system studies, A.D.Sakharov also worked on a cylindrical system, in which as thermonuclear fuel was to be used heavy water.
However, as early as November 1948, member of I.Ye.Tamm's group issued a report suggesting that the layer-cake system should use new thermonuclear fuel, namely lithium-6 deuteride.

The concept of "a layer-cake under sakharization", as well as the concept of lithium-6 deuteride application, the "first" and the "second" concepts as A.D.Sakharov called them in his *Reminiscences*, were those very key ideas, which later formed the basis for the development of RDS-6s, the first Soviet H-bomb. However, despite the clearness of the layer-cake's initial physical concepts formulated in 1948, development of an actual design on their basis proved to be by far not easy and free of problems.

In June 1949, a series of meetings took place at KB-11, which addressed the progress in the development of the RDS-1, RDS-2, RDS-3, RDS-4 and RDS-5 atomic bombs and the RDS-6 hydrogen bomb.

At one of these meeting there was presented a plan of RDS-6-related theoretical and experimental studies in 1949 through 1950 drafted by A.D.Sakharov. The plan's theoretical part consisted of two sections: 1) studies of stationary detonation wave propagation in layer-cakees; 2) theoretical research into high-temperature deuterium detonation feasibility. Noteworthy is that among numerous sub-sections, section 1) of the plan contained the following one: "study the possibility of the RDS-6 systems' reactivity enhancement by means of explosive-driven compression". The basic idea of this statement was that the initial layer-cake concept implied the feasibility of nuclear detonation in an uncompressed system consisting of uranium and thermonuclear fuel.

A resolution of the Soviet Council of Ministers dated February 28, 1950 concentrated the entire H-bomb effort at KB-11. In compliance with this resolution, the group of I.Ye.Tamm was sent for permanent work to Arzamas-16. A.D.Sakharov arrived at Arzamas-16 on March 17, 1950. The transfer of I.Ye.Tamm's group to Arzamas-16 marked a new phase of the RDS-6s project, namely materialization of basic concepts.

3.5. Development of the RDS-6s Thermonuclear Device at KB-11

The RDS-6s developed at KB-11 in 1950-1953, which was the first Soviet thermonuclear device, was a spherical system composed of uranium and thermonuclear fuel layers surrounded with HE. To enhance the energy release of the device there was used some amount of tritium. Using today's terminology, the RDS-6s was a single-stage system.

As pointed out in *Who if not me? A.D.Sakharov. Sketches to the Scientific Portrait* by V.I.Ritus, "the major task was to use the energy released by an atomic bomb explosion to heat and ignite heavy hydrogen (deuterium), i.e. to start thermonuclear reactions

$$D + D = H + T + 4\ \text{MeV}$$

$$D + D = H + He^{3} + 3.3\ \text{MeV},$$

as well as other energy-liberating reactions, which are, consequently, able to sustain themselves. It might seem, one needs insert into the bomb a layer of deuterium between fissile materials (a sphere of U^{235} or Pu^{239}) and surrounding it HE, whose shaped explosion forces the fissile material to change its state from subcritical into supercritical. It appeared, however, that deuterium had no time to get sufficiently heated and compressed, and almost no thermonuclear reaction occurred. In order to increase the "burnt" fraction of deuterium, A.D.Sakharov suggested that deuterium in the proposed design be encased in a shell of ordinary natural uranium to moderate the spread and, most important, considerably increase deuterium density. This concentration growth occurs due to the above-described process of "sakharization". As a result of the "sakharization", "the uranium sphere, whose density is twelve times as high as that of ordinary HE, enables a ten-fold increase in the density of deuterium, and, consequently, in the rate of the thermonuclear reaction".

"The higher rate of the D+D reaction leads to a noticeable formation of tritium, which immediately enters in the following thermonuclear reaction with deuterium

$$D + T = H + He^4 + 17.6 \text{ MeV},$$

whose cross-section and energy release are a hundred times and five times, respectively, as high as those of the DD-reaction. In addition, nuclei of the uranium shell are fissioned by fast neutrons produced by the DT-reaction and greatly contribute to the explosion yield. This very fact determined the use of uranium in the shell in preference to any other heavy material (for example, lead).

The rate of the thermonuclear process in deuterium might be greatly increased by replacing part of deuterium with tritium from the very beginning. But tritium is very expensive and, in addition, radioactive. Therefore, V.L.Ginzburg proposed that, instead, there should be used Li^6, which, when exposed to neutrons, efficiently produces tritium in the following reaction:

$$Li^6 + n = He^4 + T + 4.8 \text{ Mev}.$$

Use of lithium deuteride (LiD) as thermonuclear fuel resulted in a radical increase of the rate of the thermonuclear process and fission-caused energy release from the uranium shell, which is many times as high as thermonuclear energy release.

These are the physical concepts underlying the earliest modification of our thermonuclear weapons".

Prior to the outset of the heterogeneous system project, "the group of Ya.B.Zeldovich intended to fuel the thermonuclear device… with liquid deuterium (probably, mixed with tritium). Sakharov advanced another concept – a heterogeneous system with alternating layers of light (deuterium, tritium and their chemical compounds) and heavy (U^{238}) materials, which was called "a layer-cake". Teller appeared to have expressed the same ideas in 1946, but the U.S. project originally developed in another direction that proved to be a dead end.

What are the advantages of such a layer-cake? First, it allows implementation of the "fission-fusion-fission" principle necessary for explosion energy enhancement.

DT-reaction neutrons with the energy exceeding the fission threshold of U^{238} split the latter and cause liberation of additional energy. But even more important is that the low thermal conductivity of uranium enables reduction of heat outflow from the bomb material and manifold compression of the light material located in the immediate neighborhood of uranium and heated up to a temperature of tens of millions of degrees (as a result of the above-mentioned “sakharization”). This is what is necessary to increase the rate of fusion. If, in addition, the layer-cake is reinforced with lithium, neutrons will transform the latter into tritium, which, as mentioned above, is a rather efficient participant of the thermonuclear reaction.

The idea to use Li^6 in the layer-cake was put forward by V.L.Ginsburg.

I.V.Kurchatov was correct in sizing up the prospects of Li^6 application and promptly arranged its production. As a result, the Soviet Union was the first state to use it in the tests of hydrogen weapons.”

As pointed out by A.D.Sakharov in his *Reminiscences*, “preparations for the first thermonuclear warhead tests took a considerable part of effort of the site in 1950 through 1953, as well as that of other institutes and enterprises of our branch and numerous attracted institutions. This was a project, which, in particular, included experimental and theoretical studies of explosion gas dynamics and neutronics, engineering work in the direct meaning of this word, development of the device’s automatic control systems and electric circuitry, unique equipment and novel techniques for physical process recording and yield measurements.

A tremendous amount of effort involving a lot of people and great material expenditures were necessary to produce the materials for the device and carry on other industrial and technological work.

Theoretical groups played a particular role in the preparations for the first thermonuclear tests. Their task included identification of the key lines of device development, evaluation and general theoretical detonation-related studies, choice of device modifications and supervision of specific explosion calculations for various options. During those years the calculations were performed using numerical methods by special groups of mathematicians established on the basis of some research institutes.

Theoretical groups also played an important role in the identification of tasks, results analysis, discussion and coordination of almost all above activities carried out by other divisions of the site and attracted institutions.”

General supervision of the RDS-6s project was exercised by I.V.Kurchatov. Yu.B.Khariton was Chief Designer and first-hand Project Manager.

Of particular significance in the RDS-6s project was numerical modeling. Most of the calculations were performed in Moscow by teams headed by A.N.Tikhonov, K.A.Semendyayev and L.D.Landau.

Since April 1953 these activities have been concentrated in a specially established Moscow institute, Department of Applied Mathematics, under the direction of M.V.Keldysh.

In charge of calculations at KB-11 were teams of mathematicians headed by N.N.Bogolyubov and V.S.Vladimirov.

An important aspect of the RDS-6s development was constituted by experiments to study neutron processes in layer-cake-imitating critical assemblies and assemblies with a 14-MeV neutron source.

Leader of the RDS-6s field tests was K.I.Shchelkin. I.V.Kurchatov exercised scientific leadership of the tests.

An important thing was that RDS-6s was a transportable bomb, which could be carried by delivery means, i.e. it was the first sample of thermonuclear weapons.

The RDS-6s was tested on August 12, 1953 at the Semipalatinsk testing ground. It was the fourth testing in a series of nuclear tests the Soviet Union had conducted since August 29, 1949. The RDS-6s tests proved to be an imperishable milestone in the history of the Soviet nuclear military equipment development. The experimental energy release of the RDS-6s was equivalent to approximately 400,000 tons of TNT. The design of the RDS-6s implied the possibility of its further large-scale production.

The RDS-6s project created a theoretical and engineering foundation, which then underlain the development of an incomparably more efficient and qualitatively new device - a two-stage H-bomb.

3.6. Development of the RDS-37 Thermonuclear Bomb

The development of a new physical principle for the Soviet thermonuclear weapons and building of the first thermonuclear bomb based on this principle, designated RDS-37, was full of dramatic events.

The new principle came into the world owing to intensive efforts in other prioritized fields of thermonuclear weapons research and development. As can be seen above, these fields included studies of the uncompressed cylindrical system with liquid deuterium, which was expected to host nuclear detonation of deuterium caused by a nuclear explosion, as well as development of the RDS-6s, a spherical thermonuclear layer-cake-like warhead compressed by a HE explosion.

Some participants of the Soviet thermonuclear project became aware of the necessity of two-stage H-bomb development before the tests of the RDS-6s single-stage H-bomb.

Step by step, it became clear to some scientists and specialists that RDS-6s and other devices of this type could not finally solve the problem of high-efficiency thermonuclear weapons development. This was attributed to the fact that thermonuclear fuel and uranium layer compression, which could be achieved in the design of the RDS-6s-type, was relatively low. It was clear that the layer-cake to some extent settled down the problem of a thermonuclear unit, rather than the problem of a thermonuclear warhead in general. In 1952, V.A.Davidenko, leader of the nuclear-physics division of KB-11 at that time, started active advocating the necessity of developing a two-stage thermonuclear warhead, in which compression and detonation of the thermonuclear core similar to the RDS-6s warhead would be driven by an autonomous nuclear explosion.

In 1953 A.P.Zavenyagin and D.A.Frank-Kamenetsky proposed thermonuclear warhead schemes based on this principle

In January 1954, Ya.B.Zeldovich and A.D.Sakharov forwarded to Yu.B.Khariton a memo evaluating operation of a two-stage thermonuclear device.

In the draft design of the thermonuclear warhead discussed in the memo of Ya.B.Zeldovich and A.D.Sakharov, similarly to other earlier considered designs of two-stage thermonuclear warheads, the thermonuclear part was to be compressed by gas-dynamic jets brought about by the primary atomic warhead, i.e. implied was utilization of mechanical energy of the primary nuclear explosion. Understanding of great difficulties conjugated with this approach to the development of a thermonuclear warhead made scientists less optimistic and enthusiastic.

However, in spring 1954, the course was radically changed towards a two-stage system based on the principle of radiation implosion.

This happened as one became aware of the possibility to produce a considerable amount of radiation in the primary warhead to be used for boosting the thermonuclear section to an explosion. By that time the opportunities of enhancing the yield of the RDS-6s single-stage thermonuclear device were definitely established to be rather limited. Along with this, the demand for a domestic thermonuclear bomb with a yield many times as high as that of the 1953 bomb, became clear as there appeared announcements of the many-megatons' range of a U.S. thermonuclear device exploded in 1952 (Mike test).

On December 24, 1954 there took place a meeting of the scientific and technical board of KB-11 chaired by I.V.Kurchatov in the presence of V.A.Malyshev, which discussed the progress in the development of high-yield thermonuclear devices.

At this meeting Ya.B.Zeldovich made a report on the thermonuclear device based on the new principle. In his presentation after the report, I.Ye.Tamm pointed out the discussed breakthrough in the nuclear weapons development to rest upon a clear physical concept – radiation-driven compression. In their reports, I.V.Kurchatov and Yu.B.Khariton noted that the two-stage design opened wide opportunities as to the development of thermonuclear warheads, whose utilization should be started as soon as possible. Yu.B.Khariton suggested that in 1955 there should be conducted model tests of a thermonuclear bomb using the new physical scheme. As applied to the two-stage hydrogen bomb development, the meeting adopted a resolution approved by V.A.Malyshev, the concept of which is specified below.

1. The leaders of KB-11 were to submit a plan of work on the two-stage scheme with an explanatory note to the Ministry of Medium Machine Building.
2. Permission was given to start the development of the two-stage thermonuclear bomb in order to verify its principle, and preparations for, and conducting its tests in 1955 at the Semipalatinsk testing ground prior to the plan approval.

A task order for devising the RDS-37 thermonuclear bomb was issued by the theoretical physicists on February 3, 1955. By that time, the decisive stage of its computational and theoretical feasibility studies had been completed.

However, the theoretical studies and calculations, as well as design specification of the RDS-37 continued right up to the final putting-together and sending the bomb to the testing ground. On March 2, 1955, A.P.Zavenyagin, new Minister of Medium Machine Building, approved a plan of the final project phase.

On May 27, 1955, there was a meeting convened at KB-11 involving A.P.Zavenyagin. The meeting discussed the status of the RDS-37 project. Ya.B.Zeldovich addressed the meeting with a report. Based on the results of the meeting, there was drafted and signed a resolution of the Minister, which approved a scheme of the RDS-37 experimental bomb-device proposed by KB-11.

An important contribution to the preparations for the RDS-37 tests was made by a commission chaired by I.Ye.Tamm. The commission included V.L.Ginzburg, Ya.B.Zeldovich, M.V.Keldysh, M.A.Leontovich, A.D.Sakharov and I.M.Khalatnikov.

A report the commission had prepared by June 29, 1955 stated that the new principle uncovered absolutely new opportunities in the nuclear weapons development. It enabled materials compression down to such high densities, which were in no way achievable using ordinary HE on the required scale. One could expect the new principle to allow the development of efficient super-high-yield thermonuclear warheads and substantial reduction of the cost of smaller-yield warheads. Upon detailed evaluation of the theoretical studies and calculations of the RDS-37 warhead design proposed by KB-11, the commission confirmed the appropriateness of its field testing.

The intensive work on this challenging project was crowned with successful tests of the RDS-37 at the Semipalatinsk testing ground on November 22, 1955.

The bomb was dropped from an airplane. Its distinguishing features were not only engineering solutions related to the implementation in it of a new physical principle, but also certain inheriting from the 1953 RDS-6s of some design features, namely, using lithium-6 deuteride, as well as using new unconventional materials and structural components, which enhanced the probability that the bomb would perform its rated duty. These features also included using in the primary warhead of a fissionable material with reduced neutron background, as well as its relatively large size, which made the problem of symmetric compression of the thermonuclear stage easier to solve. One of the design features of the tested RDS-37 modification was artificial reduction of its yield in order to ensure the safety of population. But it still remained a megaton bomb. The experimental yield, somewhat higher than expected, proved to agree well with the calculated value.

The successful development of the next-generation thermonuclear bomb was a key point in the Soviet nuclear weapons program. According to A.D.Sakharov, “the tests was a crown of the many-years’ effort, a triumph that cleared the way toward the development of a family of devices with different, but equally high, performance”.

Let us discuss some aspects of the RDS-37 project.

The RDS-37 warhead was designed as a pilot warhead to verify the new principle. The basic requirement kept in view at its development was high reliability. It was implied that the RDS-37 tests involving measurements of the explosion yield, compression time of the thermonuclear stage, as well as radiochemical and other measurements would enable verification of calculations of all new processes and the entire concept, and development in the nearest future of a series of different-size efficient high-yield H-bombs.

The RDS-37 was the first warhead in the above-mentioned series, which underwent detailed calculations. An important thing about the development of the RDS-37 was a tendency toward avoiding additional novelties except for those absolutely unavoidable. Some of the approaches to the RDS-37 warhead design optimization became clear prior to the RDS-37 warhead tests. It was, however, decided, that most of the improvements, which required additional time, were negligible as compared to the breakthrough in the form of the implemented new principle and verified calculations of the new physical processes that occurred during the explosion based on the new principle.

In the development of such a sophisticated system, which is the RDS-37 thermonuclear warhead, of special value was contribution made by numerical modeling. In some cases, the calculations of equations in partial derivatives radically changed the concept of this or that part's operation or of the role of this or that modification in the system. These calculations were mostly conducted by the Department of Applied Mathematics at the Moscow Institute of Mathematics of the Soviet Academy of Science under the general leadership of M.V.Keldysh and A.N.Tikhonov. Most of the calculations were made using the Strela electronic machine. There were fulfilled rather challenging tasks of developing computational methods, programming and arranging the process.

The development of the RDS-37 involved a great amount of engineering, experimental and technological work conducted under the leadership of Chief Designer of KB-11 Yu.B.Khariton.

3.7. Comparison of the Early U.S. and Soviet Thermonuclear Weapons

It is interesting to compare the first steps in the thermonuclear weapons development projects of the Soviet Union and the United States. As we saw, in the Soviet Union this program initially comprised the development of two thermonuclear devices: a single-stage layer-cake, RDS-6s and a two-stage radiation-implosion device, RDS-37. The first thermonuclear device was developed in 1950-1953 and tested on August 12, 1953. The second thermonuclear device was developed in 1954-1955 and tested on November 22, 1955. The energy release of the RDS-6s was 400 kt, which was ten times as high as that of the most powerful Soviet atomic warheads developed by then. The energy release of the RDS-37 was 1.6 Mt, at that, it was obtained in an experiment with the yield artificially reduced for safety reasons. According to their design, both warheads were transportable air bombs, and RDS-37 was tested by dropping from a carrier airplane.

The U.S. thermonuclear program included the George test, the first thermonuclear experiment conducted on May 8, 1951 and aimed at verifying the radiation-implosion principle components (energy release was 225 kt) and the Mike shot, which tested a two-stage system using liquid deuterium as thermonuclear fuel. It was a non-transportable device with a mass about 75 tons. The energy released in the test was 10.4 Mt.

The next steps in the thermonuclear weapons development were made by the United States in 1954. February 28, 1954 saw the Bravo test, in which as thermonuclear fuel served lithium deuteride (with a 40-% enrichment in the isotope Li^6). The mass of the device was about 10.6 tons, length 456 cm and diameter 137 cm.

The energy release of the explosion was 15 Mt, which was two and a half times higher than the value they had expected (6 Mt).

On March 26, 1954, during the Romeo test there was exploded a EC17 thermonuclear device. As thermonuclear fuel was used lithium deuteride mixed with natural lithium (7.5% enrichment in the isotope Li^6). The mass of the device was about 18 tons, length 571 cm and diameter 156 cm. The energy release of the explosion was 11 Mt.

During the Union experiment on April 25, 1954 there was tested a EC14 thermonuclear device with lithium deuteride (95% of Li^6) as thermonuclear fuel. The mass of the device was about 12.5 tons, length 383 cm and diameter 156 cm. The energy release of the explosion was 6.9 Mt.

May 4, 1954 saw the Yankee experiment with a EC24 thermonuclear device. In its general features, the tested device was close to the device tested during the Romeo experiment. The test released 13.5 megatons of energy.

During the Nectar test conducted on May 13, 1954, there was detonated a smaller-size and -mass thermonuclear device, which served as a prototype of a B15 device. The mass of the device was about 2.8 tons, length 280 cm and diameter 88 cm. The energy release of the tests was 1.6 Mt.

These five tests of 1954 formed the basis for the further thermonuclear program progress in 1956, when during the Cherokee test there was exploded a warhead for a B-15 bomb with a 3.8-Mt yield (the mass of the device was 3.1 tons, its length and diameter were 345 and 88 cm, respectively). During the 1954 tests the thermonuclear devices were detonated on the surface or aboard a barge, whereas the Cherokee thermonuclear device was for the first time dropped from an airplane.

As a result of the thermonuclear weapons competition between the Soviet Union and the United States during the period of interest, in 1955 the Soviet Union caught up with, and in some aspects even surpassed the United States. These aspects included the following ones.

The Soviet Union was the first to use highly efficient thermonuclear fuel, lithium-6 deuteride - in 1953 in the single-stage and in 1955 in the two-stage thermonuclear device; the United States tested in 1952 the two-stage liquid-deuterium thermonuclear device and in 1954 the two-stage thermonuclear devices with lithium deuteride.

In the early thermonuclear tests the Soviet Union achieved high accuracy of yield calculations and theoretical predictions.

The belief in the reliability of the 1955 first two-stage thermonuclear warhead was so firm, that for the public safety reasons, the yield of the thermonuclear explosion was deliberately reduced to a half. The Soviet Union was the first to drop a thermonuclear bomb from an airplane in 1955. The United States conducted such tests in 1956.

Chapter 3

Development of the Soviet Nuclear Weapons Program

Contents

1. Activities Intended to Enhance the Characteristics of Nuclear Weapons

1.1. Totsk Military Exercises in 1954

On September 14, 1954 RDS-2 bomb was exploded for the second time during unique military exercises using nuclear weapons that were arranged at the military firing ground near the settlement of Totsk.

The exercises were scheduled for the autumn of 1954. Marshal of the Soviet Union G.K.Zhukov was appointed to be in charge of them. The troops to participate in the exercises started gathering near Totsk station, South Ural Mountains, a few months before. After a time there appeared a kind of encampment in the steppe. About 45 thousand people took part in these military exercises. Training and preparation of the positions for offensive started. The exercises were carried out in the locality approximated to that where the operation was to be performed. The troops had to dig shelters, trenches, to build roads and arrange such military equipment as aircraft, tanks, guns, machinery in this locality. Besides, they had to act constantly in tactical exercises and marches and to wear gas-masks at that. This was very difficult since that year turned out to be extremely hot. The temperature was about 30-40°C. Exhausting training started in May and lasted till late August. By September 1, 1954 everything was ready for the operation.

On the eve of tests the training area was visited by the First Secretary of the Central Committee of the Communist party of the Soviet Union N.S. Khrushchev, the Minister of Defense of the Soviet Union N.A. Bulganin and I.V. Kurchatov. The site for the intended explosion was turned into a restricted area having a radius of 8 km.

Five days before the training tests started all the troops had been withdrawn from the restricted area. Its borders were provided with outposts. Since this point on one could only enter the restricted area through the check-point after showing special permission documents. The inhabitants of the nearest settlements had been evacuated.

By the morning of September 14, the “defenders” occupied the regions being at a distance of 10-12 km from the intended atomic explosion ground zero. The “attackers” settled down beyond the river to the east of the explosion site.

At 9:20 the supervisor of the exercises heard the report on the meteorological situation and took the decision to set off an explosion. The aircraft crew were ordered by radio to release the atomic bomb onto the test field. The intended explosion ground zero had the form of a big white cross made of reflectors.

Three aircraft appeared in the sky. One of them was carrying the atomic bomb. Ten minutes before the atomic blow was delivered the “atomic alarm” had gone off and the troops had occupied shelters and dug-outs.

At 9:35 the atomic explosion took place at an altitude of 350 m. The explosion energy release was 40 kt. In 5 minutes after the atomic explosion, artillery preparation and bomb attacks of the air force started. The explosion ground zero was not affected by the artillery. After artillery preparation and air force attacks the troops received the order to move towards the explosion ground zero.

At 10:10 the attackers took up the conventional enemy′s positions. The reconnaissance detachments and the radiation survey troops were sent forward. At about 12:00 the advanced detachment having managed fire and blockage sites got to the atomic explosion area.

In 10-15 minutes the first echelon subunits of the attackers started moving towards the same area, but to the north and south of the epicenter. The contamination region was marked by warning signs put by the reconnaissance patrols, and the offensive subunits could be guided in the radiation situation.

In the course of these exercises atomic strikes were simulated twice by blasting conventional explosives.

The military exercises lasted all day long. At 16:00 the retreat was sounded. After the exercises had been over, the personnel were checked, radiation monitoring of people and military equipment was organized. All the subunits having acted in the atomic explosion area were subjected to sanitary inspection and treatment. The uniforms were replaced and the military equipment was decontaminated.

The unique military exercises using nuclear weapons came to an end.

1.2. First Steps Towards Improvement of Tactical Weapons

The nuclear device developed for T-5 torpedo was also put into service as a part of the warhead (WH) for the antiaircraft missile ZUR-215. Record tests of ZUR-215 having a nuclear WH were conducted in the air space (at an altitude of about 10 km) at the antiaircraft test site of the Ministry of Defense (MOD) on January 19, 1957. The explosion energy release was 10 kt. This missile launching and the nuclear device explosion were a final stage of the state flight tests of ZUR-215 missile. As opposed to the previous nuclear explosions set off in the near-ground space, ZUR was exploded at a high altitude. Two radio-controlled target aircraft IL-28 that were at a distance of about 600-1000 m from the ground zero were destroyed. This explosion made it possible to arrive at the basic physical parameters of explosions set off at rather high altitudes.

The warhead of the tactical ballistic missile “Mars” was developed with the same nuclear device. Its range was 8-18 km and it had a mobile launcher.

By about 1957 the plants of the USSR nuclear complex had built up a rather great amount of weapon-grade uranium-235, therefore the question arose whether it was possible to use it as a part of nuclear filling for atomic devices in combination with or without plutonium. To this end the implosive atomic device was made based on RDS-4 charge design, where only uranium-235 was used as a nuclear fuel. To initiate a chain reaction, an external pulse neutron source was provided for. This device was tested successfully and after that it was put into service as a part of warheads for:

- The tactical powder ballistic missile “Filin” having the range from 8 tp 18 km and a mobile launch;
- The tactical ballistic liquid-propellant missile R-11M having 150-km range and a mobile launch;
- The ballistic missile R-11FM (of R-11M type) for submarines and cruisers.

In 1956 the nuclear device for the artillery shell was designed and tested. It was intended for artillery systems of 406.4 mm “Kondensator” gun mounted on self-propelled artillery units and for 420 mm mines of “Transformator” mortar mounted on mine-throwing self-propelled units. This was a rather formidable weapon and its range was as high as 20-25 km. It was many times demonstrated during military reviews on Red Square. The nuclear device was made by the team with V.M.Nekrutkin in charge that was specially organized within the design bureau KB-11. Academician M.A.Lavrentiev was responsible for scientific supervision of the activities aimed at providing artillery arms with nuclear devices.

The nuclear device for the artillery shell differed from the previously developed ones in design. This was the first shockproof implosive atomic device. The main problems of this development were related to a great decrease in the nuclear device middle as compared with the previously made and tested designs as well as to providing a mechanical device resistance to effects of dynamic overloads resulting from the shell acceleration in the artillery gun bore. The aim to make the most use of the assigned dimensions for the HE charge and to ensure the required overloads caused the lens focusing system to be refused.

Proving ground tests were a success. By 1959 the atomic shell had been put through the entire cycle of gas dynamic firing tests and all the documents were prepared for its serial production. However, tactical powder ballistic missiles with the nuclear weapons “Filin” and “Mars” that had the range almost similar to that of

“Kondensator” and “Transformator” guns had been adopted for service by that time. Therefore, application of the atomic shell was no longer topical and the documents “were put on the shelf”. The team that had developed the atomic device was broken up. Later the projectile subject matter was passed on to the Scientific Research Institute (NII)-1011.

1.3. First Steps Towards Improvement of Thermonuclear Weapons

As has been mentioned in chapter 2, the first RDS-6s thermonuclear device was tested successfully on August 12, 1953. The design of RDS-6s device was developed on the condition that it could go into the ballistic body of the first atomic bomb RDS-1 being 1.5 m in diameter. The device yield was 20 times as high as that of RDS-1.

Some amount of tritium was used in the energy releasing assembly of RDS-6s device to ensure a successful result. In terms of a war device this reduced greatly its operational and ecological characteristics as compared with an atomic device. Therefore in the future the tritium component was going to be excluded from the hydrogen device.

After RDS-6s had been tested, the work aimed at developing a war device based on its design was placed on a broad footing in KB-11. It was intended:

- For the reentry vehicle of the intercontinental ballistic missile R-7 being developed in the Special Design Bureau (OKB) under academician S.P.Korolyov;
- For the air bomb of RDS-6s type.

As opposed to RDS-6s design, tritium was excluded from the air bomb device but its energy release was reduced accordingly.

The air bomb was successfully tested at Semipalatinsk test site on November 6, 1955. The explosion yield of 250 kt was close to the estimated one, but less than the yield of RDS-6s.

The air bomb had the maximum diameter identical to that in RDS-1 (1.5 m). But it was longer than the RDS-1 bomb and it was intended for delivery on the new TU-16 bomber being deployed for service at that time in the Air Force of the USSR instead of TU-4. As compared with TU-4, the aircraft TU-16 had a longer bomb hatch, which made it possible to apply air bombs with nuclear devices of the same diameters as those of the first RDS bombs (1.5 m), but with a greater length. Thus, the standard length to diameter and specific cross-section load ratios conventional in bomb-building were maintained, which in its turn increased target bomb throwing characteristics.

During testing the new air bomb was released from the aircraft TU-16 onto the ground target. The altitude was 12 km. The explosion took place at the specified altitude of about 1000 meters.

In these tests the effects were studied that were produced by the powerful nuclear explosion upon the war materiel such as aircraft, artillery, tanks as well as dwelling and production buildings, for this purpose having been erected at the test site. In particular, a two-storeyed brick house 2,700 m away from the ground zero was destroyed completely. At a range of 5,100 m the similar house underwent less serious destruction. The railway single-span bridge about 800 m away from the ground zero was overturned and thrown away by 10 m.

According to the Government′s resolution, R-7 missile required the device a few times as powerful as the first tested hydrogen device of RDS-6s.

Calculation estimations showed that the device of RDS-6s type design with the required yield would have extremely large overall dimensions and weight. In this connection it was decided for R-7 missile to speed up the yield of RDS-6s device in its tritium-free variant by applying a significant mass of fissile materials in the central energy releasing assembly.

The device was designated RDS-6SD. It represented further development of physical ideas successfully checked during RDS-6s device tests.

In the course of RDS-6SD development it soon became clear that the physical layout of RDS-6s could not be used to solve the problem of creating a highly efficient thermonuclear device.

Design of powerful thermonuclear devices according to the two-stage pattern made it possible to renounce a low-promising way of their creation according to the single-stage pattern. The latter required impermissibly large masses of fissile materials to produce a high yield (several megatons) within the limited overall dimensions. Serial production of such devices was unreal in the middle 50s.

The basic property of the two-stage pattern was rather wide opportunities for optimization of arrangement characteristics of devices in nuclear weapons.

The two-stage pattern of thermonuclear devices allowed the specific yield of weapons (the weapon yield to its weight ratio) to be increased greatly.

Development of the device for equipping the reentry vehicle of R-7 missile had a dramatic character. RDS-37 successful explosion was followed by a series of failures of thermonuclear assemblies of the two-stage devices being developed in KB-11 for R-7 missile reentry vehicle. This was the testimony to insufficient notions of the processes that took place in the devices of RDS-37 type.

At the same time NII-1011 was also engaged in developing high-yield thermonuclear devices based on RDS-37 design. On April 10 and 16, 1957 NII-1011 tested two thermonuclear devices at the Semipalatinsk test site. The tests of April 10, 1957 showed good results.

Clearly the question arose of whether to use these results for development of the device for R-7 missile reentry vehicle that was under way in KB-11. In late 1956 a meeting with the tests of 1957 on the agenda was arranged under supervision M.G.Pervukhin, acting minister of Medium Machine Building.

The reports of Ye.A.Negin (KB-11) and V.F.Grechishnikov (NII-1011) “On Selection of the Nuclear Warhead for R-7 Missile” were heard. The thermonuclear assembly version developed by KB-11 was discussed.

As a result, the following decision was taken:

- “to approve the device of KB-11 for R-7 missile that consists of NII-1011-produced thermonuclear assembly and the initial atomic device based on RDS-4;
- to test the device for its full explosion yield”.

The device for R-7 missile was tested in the air bomb body. Because of a high estimated yield of the thermonuclear device and in accordance with the decision to conduct a full-scale explosion, it was tested at the Northern proving ground. The test field 260 km away from the test site base was chosen for the experiment.

On October 6, 1957 the bomb was released from TU-16 aircraft. The altitude of bombing was ~11,500 m. The explosion took place over the target at the altitude of ~2100 m. At that moment a dazzling bright ball of fire was produced.

The generated experimental yield of the thermonuclear device of 2.9 Mt was higher than the estimated one by 20%.

When the reentry vehicle of R-7 missile was designed, flight and design tests were carried out in addition to land-based laboratory and design complete development efforts. Their aim was to define its design condition, the temperature effects produced upon it, displacement and deformation of assemblies under real overload and temperature conditions generated during the reentry vehicle flight. In performing the flight and design tests, the appropriate telemetric information was transmitted to the ground registration systems. The flight tests showed that the reentry vehicle structure and the device were intake. The values of overloads, temperature effects and displacement of the assemblies were within the permissible limits. This made it possible to conclude on a high reliability of R-7 missile reentry vehicle.

The first launch of R-7 missile within the framework of flight and design tests was made on August 21, 1957 from the space-vehicle launching site Baikonur. This space port was built by the Government decree in 1955. It is situated in the desert locality of Kzyl-Orda region, Republic of Kazakhhstan.

The reentry vehicle of R-7 missile with the device weighed ~5400 kg. In 1957 it was put into operational service for the Soviet Army.

The first R-7 intercontinental ballistic missile in the Soviet Union provided with the thermonuclear device had a range of fire about 8000 km. A total of four missile complexes was deployed. All of them were bulky, very expensive and had a low level of combat readiness.

At this period of time the leadership of the country took all possible measures to develop ICBM of a new generation for the Soviet Army.

1.4. Thermonuclear Devices of the Second Generation

The pattern of the thermonuclear device arrangement in R-7 missile reentry vehicle (RV) had great drawbacks explained by peculiarities of interdepartmental relations. The device was not an independent unit, which was not convenient both to the reentry vehicle and the device development engineers.

Aspiration of the R-7 missile nuclear reentry vehicle developers to achieve the greatest possible weight reduction in order to ensure the specified range of fire predetermined the circuit diagram for this reentry vehicle arrangement where the individual reentry vehicle body fragments fulfilled the power device body functions. Such an arrangement pattern allowed the weight expenditures for the reentry vehicle design with the device to be decreased greatly. This was done due to making the RV manufacture and assembly technology more complicated, which demanded creation of special-purpose complicated assembling equipment and establishment of interdepartmental relations.

Since KB-11 and OKB-1 belonged to different state services, complications arose that were mainly related to departmental responsibilities for complying with the technical requirements and normal functioning of the RV body members and device during operation or probable combat application.

Therefore, it was natural that the device developers aimed at creating a low-bulk thermonuclear device in the form of an independent assembly arranged in its own single body that had suitable mounting and fitting elements for securing in the armament compartment of the RV body.

At the same time the young scientists, physicists-theoreticians Yu.N.Babaev and Yu.A.Trutnev proposed an improved pattern of the two-stage device that allowed its overall dimensions to be greatly reduced. Later this pattern was used as the basis for development of the next generation of thermonuclear devices.

When developing an experimental device model, special emphasis was placed on reliability and normal operation of the structure.

The search for new approaches was directed towards:

- selection of the thermonuclear assembly materials and design;
- the system of securing the thermonuclear assembly in the device body;
- construction variants for components of the device as a whole;
- atomic initiator suspension design.

The device was successfully tested at the Northern test site on February 23, 1958. The explosion energy release was 0.86 Mt.

An important landmark in improvement of tactical characteristics and specifications of atomic and thus thermonuclear second-generation devices was implementation of Ya.B.Zeldovich′s idea to increase greatly the atomic device efficiency due to the so-called “booster” action mode. The idea of the “booster” mode was checked in a series of proving ground tests in 1957-1958. Owing to its implementation, it was possible to reduce greatly the consumption of fissile materials in the atomic initiator, to increase reliability of the device action.

Thermonuclear devices having atomic initiators with the “booster” mode were adopted for service in the early 60s by strategic missile systems and the Navy (submarines) where they operated for a long time.

On March 31, 1958 the Supreme Soviet of the Soviet Union passed a resolution on unilateral termination of all nuclear weapon tests. However, the United States and Great Britain did not follow the USSR′s example and in April of 1958 they started fulfilling a large program of nuclear tests aimed at improving their nuclear weapons.

Under these conditions the Soviet Union had to lift the unilateral moratorium and declared that it had a right to perform test explosions “in one to one proportion” with respect to the total number of the explosions having been set off by both powers since March 31, 1958.

Speaking at the XXI Congress of the CPSU in 1959, I.V.Kurchatov said: “During the spring and summer of 1958 the United States conducted more than 50 test explosions. This fact made our country resume nuclear tests in the autumn of 1958. By the way, these tests turned out to be very successful. They showed a high effectiveness of some new principles worked out by the Soviet scientists and engineers. As a result, the Soviet Army has gotten still more powerful, more perfected, more reliable, more compact and less expensive atomic and hydrogen weapons.”

As opposed to the first device specially designed for R-7 missile reentry vehicle, new devices were developed without keeping after the associated weapons (reentry vehicles) since reentry vehicle carriers were under development at that time and the requirements specified for both weapon and device parameters were not determined. Since then a specific device design order started establishing. It existed for a long time: development of devices not for a specific carrier, but according to the classes or mass categories.

On the one hand, such an order speeded up improvement of device characteristics during numerous air tests. On the other, it created conditions for nonproductive costs, pile-up of unnecessary ranges of devices.

On October 31, 1958 the Soviet Union, the United States and Great Britain started negotiations in Geneva on cessation of nuclear tests. Since that time and during almost three years the countries participating in these negotiations refrained from proving ground tests.

On November 3, 1958 the Soviet Union carried out the last test of the period under consideration. From November 3, 1958 till September 1, 1961 the trilateral moratorium with the United States and Great Britain was observed, whereupon the Soviet Union resumed testing.

However, it should be noted that by that time the United States had already conducted 196 nuclear tests, 21 tests had been carried out by Great Britain, which in total exceeded the number of nuclear tests in the USSR by a factor of 2.6. The United States had already started complete development of the new technology for nuclear underground tests thus getting ready in advance for the activities under atmospheric nuclear testing ban conditions. By the moratorium of 1958 they had made 20 experiments of this kind both in tunnels and boreholes (not including the excavating explosion). The total energy release of the U.S. and Great Britain nuclear tests (about 125 Mt) exceeded by that time the total energy released from the USSR nuclear tests (about 27 Mt) by a factor of 4.6. In 1953 through 1958 the United States implemented the extensive program of thermonuclear weapons production. At this period of time the number of warheads in the U.S. stockpile increased from 1170 to 7345 and their total energy release increased from 73 Mt to 17,300 Mt (by a factor of 240). This was the nuclear arsenal capable to destroy the Soviet Union. Therefore, in spite of the outstanding progress made by our specialists in development of nuclear weapons, the problem of failing to keep up with the United States was still a challenge and objective possibilities for the U.S. atomic pressure did exist. It was the time when the moratorium on nuclear tests began.

1.5. Moratorium of 1958-1961

On November of 1958 the trilateral moratorium on nuclear testing came into force. By that time the basic physical and design approaches to development of modern atomic and thermonuclear devices had been confirmed. Serial production of the components for nuclear devices and weapons was put into effect, updated devices as parts of nuclear weapons were included in the inventory of the Soviet Army and Navy. There appeared the first results of nuclear weapons (NW) operation by troops. Urgent additional investigations were required, special design and technological measures had to be taken to eliminate deviations in the physical and mechanical design properties that manifested themselves in operation and to remove mechanical defects inadmissible for normal operation of devices. The moratorium on nuclear tests made it possible to shift the burden of calculating, research, design and engineering activities towards solution of the existing engineering problems having a pragmatic character.

Scientific supervision of all the problems caused by development of nuclear devices and weapons in KB-11 was provided by Yu.B.Khariton, the director B.G.Muzrukov was an administrative leader.

A.D.Sakharov and Ya.B.Zeldovich were in charge of theoretical departments, V.A.Davidenko was responsible for experimental physics, N.A.Kazachenko was the head of the gas dynamics department and technological issues were the sphere of N.A.Petrov′s supervision.

The design departments were united to form two design bureaus responsible for a specific topic:

- KB-1 – design of nuclear devices. It was headed by the Chief designer Ye.A.Negin and his first assistant D.A.Fishman;
- KB-2 – design of nuclear weapons and automatics systems providing explosion of nuclear devices. It was headed by the Chief Designer S.G.Kocharyants and his first assistant Yu.V.Mirokhin.

Improvement of operation characteristics of nuclear devices was one of the first-priority tasks for the developers.

The program of improving performance of nuclear devices was changing into a long-term combined specific program that could be divided into some separate areas:

- Studies aimed at increasing physical and mechanical characteristics of the existing explosives and application of new explosives;
- Development and implementation of new safe electric detonators;
- Studies providing the possibility for a long-term operation of plutonium components as parts of nuclear devices;
- Perfection of the possibilities for complete development of nuclear devices under flight and design testing conditions;
- Improvement of structural elements ensuring a “booster” nuclear device operation mode.

1.6. Air Tests of 1961-1962

Why was the trilateral moratorium of 1958 violated?

To answer this question, we consider some events that had taken place shortly before the moratorium termination.

On January 15, 1960 the Supreme Soviet of the Soviet Union appealed to the parliaments and governments of all the states in the world to make great efforts for reduction of armaments and armed forces and banning nuclear and other types of mass destruction weapons. However, a great aggravation of the international situation happened soon that was caused by the incident with the American reconnaissance aircraft U-2. The aircraft U-2 piloted by Gary Powers was shot by the Soviet missile in Sverdlovsk region on May 1, 1960. As a consequence of the intrusion into the Soviet air space, the meeting between the leaders of the four powers such as the USSR, the United States, Great Britain and France that was to be held in Paris on May 16 was canceled.

During the time which had followed before the moratorium was broken the American reconnaissance aircraft violated the USSR borders more than once.

Of no less importance for intensification of the international tension was also the decision to erect the Berlin Wall taken in August of 1961.

On August 31, 1961 the Soviet Government made the Statement. In particular, it read:

"...people are witnessing now the ever increasing aggressive policy of the NATO military alliance... The Soviet government consider it their duty to take all necessary measures so that the Soviet Union may get perfectly ready to neutralize any aggressor if they try to make an attack... That is why the Soviet government have already taken some serious measures to strengthen the USSR security. For the same reason it has made a decision to carry out tests of nuclear weapons after this issue has been thoroughly discussed".

And then: "It is no secret that the United States are on the threshold of underground nuclear explosions and they are only looking for the first suitable pretext to start them... The Soviet government cannot disregard the fact that the United States ally in NATO, that is France, has been conducting nuclear tests for a long time already… despite the warning of the Soviet Union that it will have to resume tests if France does not stop its experiments with nuclear weapons".

The reality of the Soviet Union precarious situation consisted in the following. The United States had already got the nuclear potential sufficient for delivering a nuclear attack on the Soviet Union and turning its territory into a radioactive desert.

The Soviet Union was encircled with military air bases of the United States, the U.S. missiles were deployed even in Turkey directly bordering upon the Soviet Union.

The Soviet nuclear arsenal was a few orders of magnitude less at that time and posed no real threat to the United States: starting in 1960, only four ICBM Đ-7 missiles were deployed whose range was hardly enough to reach a target. Besides, reliability of these missiles was not high because of unstable liquid fuel and for some other reasons and they were vulnerable to a forestalling nuclear attack. Air bombs, medium-range missiles, tactical weapons being at the USSR disposal posed danger only to the U.S. NATO allies on the European theatre of war.

It was the inadequacy of the Soviet Union and United States security conditions in case of a nuclear conflict that caused the Cuban missile crisis in 1962, when the Soviet Union started deploying in Cuba medium-range missiles R-12 with megaton-class warheads.

The established actual situation made the political leadership of the country revise the existing military doctrine which placed emphasis on army operations and coordination between the branches. The new doctrine whose main provisions were set out in the report presented by N.S.Khrushchev at the meeting of the Supreme Soviet on January 14, 1960 focused attention in the military strategy on ballistic missiles with nuclear weapons that would become a decisive factor both on the European theatre of war and in the global conflict between the Soviet Union and the United States.

Thus, the national security interests set the task of eliminating the United States superiority by further improvement of domestic weapons.

As a result of the nuclear tests carried out in 1961 through 1962, the Soviet Union made a new spurt in development of a wide range of atomic and thermonuclear devices for the Armed Forces. From September 1961 till December 1962 138 nuclear tests were conducted.

By the early 60s KB-11 and NII-1011 that were scientific and production complexes by their character had increased greatly both in terms of the number of specialists on their staffs and production capacities of plants and workshops, instrumentation of laboratory and research departments. Structural transformations also took place. Administrative and functional organizations were divided into four main blocks:

- Physical-theoretical, experimental and calculating departments;
- Design bureau for development and testing of nuclear devices;
- Design bureau for development of nuclear warheads and munitions;
- Pilot production (plants).

The increased scientific and production potential and the new architecture made it possible to concentrate all efforts and means for solution of the main problem

– creation of the nuclear state shield. The proving ground tests that began in September of 1961 played a crucial role in solution of this problem. During a very short period of time new updated thermonuclear devices were designed and tested. Their estimated characteristics, the level of safety and reliability were experimentally supported.

What main problems were solved during the tests in 1961-1962?

1. Tests of thermonuclear devices for ICBM under development and other armament systems.
2. Creation of high-yield thermonuclear devices for future heavy ICBM.
3. Increase in the specific yield of thermonuclear devices having been tested before the trilateral moratorium of 1958 was concluded.
4. Development of small atomic devices having high specific characteristics.
5. Check of atomic devices for their nuclear explosion-proof character in the mode of single-point initiation.
6. Check of atomic and thermonuclear devices for their reliability.
7. Experimental verification of new physical ideas and technical approaches to improvement of components of atomic devices.
8. Proving ground tests aimed at studying the physical principles being the basis of nuclear explosion systems.

In the early 60s medium-range missiles R-14, intercontinental ballistic missiles R-16, R-9 were under development. OKB-1 was making development efforts related to solid-propellant missile RT-2.

The matter of war equipment of liquid-propellant ICBM was almost settled after successful tests in 1958. One of the purposes of 1961 tests was a great increase in the specific yield of such devices to provide further updating of the war equipment in the mentioned missiles.

To increase the specific yield, great efforts were concentrated on perfecting primary atomic initiators, reducing their weight and overall dimensions. This was the area where great progress was made. Due to stage-by-stage improvement of tactical characteristics and specifications of primary modules, the thermonuclear devices were developed that had higher specific yield values and were more perfect as far as other tactical characteristics and specifications are concerned. They were subsequently accepted for service together with their associated reentry vehicles.

On October 30, 1961 the “superbomb” whose designed yield was as high as 100 Mt was successfully tested at the Northern test site. For the test its yield was deliberately reduced to 50 Mt. The plan of creating a hydrogen superbomb and its testing were a political act, demonstration of the “justice day” weapon. At that time there were no missile carriers for such a devices, the “superbomb could not go into the bomb compartment of the aircraft carrier. Because of its great dimensions there were even some problems connected with its conventional transportation.

Nevertheless, as A.D.Sakharov wrote in his “Reminiscences”, he worried about the fact that there was no carrier for this device. And he decided that a large torpedo launched from a submarine might serve as a carrier. The enemy′s ports could become the target of the attack made at a distance of several hundred kilometers.

In the proving ground tests of 1961-1962 the parameters of a few devices whose yield was more than 10 Mt were checked. These devices as well as the “superbomb” found almost no practical application except for the high-yield device used in heavy ICBM R-36.

About 30 types of experimental thermonuclear devices, more than 10 types of atomic devices being of independent modification were verified in proving ground tests by VNIIEF development engineers alone. After testing, a number of thermonuclear devices, atomic devices and primary initiators developed by VNIIEF underwent full-scale laboratory and design complete development and were put into batch production. All of them were accepted for service for equipment of various-purpose nuclear weapons, strategic first of all.

These weapons included:

- ICBM R-16 and R-9;
- Medium-range missile R-14;
- ICBM RT-2;
- ICBM R-36;
- Tactical Army missiles;
- cruise Air Force missiles;
- air defense missiles;
- antisubmarine missiles;
- torpedoes.

Proving ground tests failed to support the estimated yield of some experimental devices. Some thermonuclear devices of certain weight categories though having even very high specific values found no real application because of the device weight and ICBM payload nonconformity.

The tests carried out in 1961-1962, especially the tests of superpower devices demonstrated great progress made by the Soviet Union in nuclear technologies. These tests resulted in a great reduction of the gap between the Soviet Union and the United States in terms of test site experiments.

By the middle of 1963, that is by the end of the atmospheric nuclear testing epoch, the Soviet Union had set off 221 nuclear explosions while the United States had made 333.

1.7. Development of Nuclear Devices under Underground Testing Conditions

In 1963 the representatives of the governments from the Soviet Union, United States and Great Britain signed the Treaty in Moscow banning nuclear weapons tests in the atmosphere, outer space, and under water. Underground tests were a new job that required a special technology for their making and creation of new methods for diagnosing parameters of an underground nuclear explosion. It was necessary to make calibration experiments providing support for the measurement accuracy. The first underground tests were devoted to solution of such problems and checking of normal operation of some low-yield mainly atomic devices.

It should be mentioned that the Soviet Union and the United States entered the Treaty of 1963 when they had very different levels of preparation for underground tests. By the time of the Treaty signing the United States had carried out 116 underground experiments from the total number of 333 nuclear tests, while the Soviet Union had made only 2 underground experiments from the total number of 221 nuclear tests.

During the air tests of 1961-1962 a great number of the basic physical ideas, circuit diagrams and characteristics of atomic and thermonuclear devices were experimentally verified. The main theoretical operation principles of atomic and thermonuclear devices were experimentally checked and supported. The leading theoreticians started loosing their interest for the ideological aspect of device development. They seemed to suppose that further perfection of the device characteristics would be mainly done at the engineering level due to optimization of mathematical simulation methods, increase in the capacity of computing facilities, development of laboratory research techniques, etc. As a consequence, Ya.B.Zeldovich moved to Moscow in 1963 and began working at the Institute of Applied Mathematics of the Academy of Sciences. Later in 1968 A.D.Sakharov gave up his post not only for the mentioned reasons, but also by the order of the Ministry leadership (this order was explained by political causes). In 1969 A.D.Sakharov was enrolled on the staff of the Physics Institute of the Academy of Sciences (FIAN).

At the initial stage of underground tests (1964-1966) the priorities in development of devices and the orientation of activities carried out by development institutes changed a little. Much consideration was this time given to prospecting activities related to industrial-purpose devices, to program research aimed at improving the properties of devices, their performance, safety, etc. This period of time was characterized by a new stage in build-up of the U.S. offensive and defensive arms. Strategic missile systems such as Minuteman and Polaris including those having multiple reentry vehicles (MRV) were being deployed. The activities related to the antiballistic missile defense system Safeguard equiped with Spartan and Sprint missiles with nuclear warheads were in full swing. The necessity of taking adequate measures made developers of domestic weapons start solving new problems connected not only with increasing specific characteristics of devices for strategic arms complexes, but also with development of devices having preset properties for tactical weapons systems, air defense (AD) and antiballistic missile (ABM) defense systems. Equipment of the computational device developing centers with new-generation machines that would allow more complicated computations contributed greatly into solution of these problems.

The main directions for improving nuclear devices starting from the mid-60s till the early 70s were as follows:

- increase in the specific yield of devices due to perfection of the thermonuclear module;
- increase in the specific yield of devices due to the primary initiator weight reduction;
- increase in resistance of devices to nuclear explosion effects (NEE);
- increase in reliability of standardized primary atomic initiators.

The 60s showed maturity of the device science and engineering. Development engineers had advanced greatly in understanding device operation processes and design of nuclear weapons. This allowed them to start developing more complicated arrangements. In 1965 they began model experiments for creating a thermonuclear device having a peculiar physical architecture that would increase the thermonuclear assembly compression level. Yu.N.Babaev was its main ideologist. The device had good arrangement parameters that made it possible to improve dimension, weight and aeroballistic characteristics of the warhead.

A few possible device diagrams were worked through. Several test site experiments were made including those that were unsuccessful at first. This might be explained by imperfect calculation techniques used at the first stage of engineering development and a weak computational basis.

In 1971 one of these devices was successfully tested for its full yield.

The year 1966, when the device having a higher specific yield and later included in the inventory of land-based missile complexes was tested, could be considered an important landmark in updating strategic devices of the period under consideration.

Putting into operation of BESM-6 machine and creation of programs that allowed making computations at a new level made it possible to obtain the specified device characteristics to a high calculation accuracy and then verify them in tests. Development of specialized devices for tactical nuclear weapons, air defense and antiballistic missile defense systems started. The plans for creating AD and ABM systems raised critical questions of survivability of nuclear devices. For this purpose a set of experiments was made to study combined effects produced by nuclear explosion radiation on weapons, devices and components.

Great efforts were aimed at development of efficient tactical devices, thorough engineering development of standardized initial atomic devices to increase reliability of the latter.

Extremely important results in terms of practical application were generated during testing in 1968-1970, when the devices of various weight categories having increased resistance to NEE and a record specific yield of improved primary initiators underwent complete development. These devices and their efficient modifications having various weights, yields and explosive capacities began service in the armed forces of the Soviet Union and were used as war equipment for strategic missiles and other types of arms.

2. Development of Modern Nuclear Weapons

2.1. Development of the Third-Generation Nuclear Weapons for Equipment of Strategic Arms at the Period from the Second Half of the 60s till the Early 80s

In the mid-60s nuclear weapons centers of the Soviet Union started perspecting calculation-theoretical and design activities aimed at updating the existing strategic thermonuclear devices and developing new types of war equipment for ICBM, SLBM as well as AD and ABM means.

Research and development efforts made in this area were in many respects promoted by research and design activities related to nuclear weapons systems that were carried on in the United States.

On July 11, 1962 the U.S. Secretary of Defense Robert McNamara made a conceptual statement saying that destruction of the military enemy forces and not civil population would be the main military objective in case of a nuclear war. This statement signified the change in the development strategy of the U.S. nuclear forces. The question was about making nuclear attacks on the Soviet strategic missiles.

This concept determined the possibility for delivering, if need be, a forestalling attack, that is carrying the first-strike nuclear attack by the United States. At the same time, the logic of the preventive strike strategy is such that the attacking party should be reliably protected against reprisal to be made by the remaining survivors. Without such protection probable losses could be admissible in military but not in political terms.

It was the combination of these two factors that governed the basic directions for evolution of the U.S. nuclear forces at that time. The strategic nuclear arsenal of the United States was developing swiftly in the 60s with its quality being improved.

The program of creating the ICBM Minuteman with single warheads was implemented. Minuteman-1À, 1Â and Minuteman-2 missiles were deployed in 1962 and 1965, respectively.

Submarines with SLBM Polaris were deployed. In late 1960 the first atomic submarine with 16 single warhead missiles Polaris À-1 was put into operation. In 1964 the third modification of Polaris missile Polaris À-3 equipped with a multiple reentry vehicle (of MRV type) and having three warheads was put into service. The multiple reentry vehicles of this type increased the combat efficiency of missiles owing to the increased number of warheads though they had lower-yield devices than those in the single warhead. At the same time, they could provide more successful getting over probable counteraction of the enemy antiballistic missile defense.

At the same period of time the studies into the possibility for developing multiple independently-targetable reentry vehicles (of MIRV type) started. A high targeting accuracy of MIRV type reentry vehicles greatly increased the efficiency of destroying silo launchers (SL) of strategic missiles. This fact imparted fundamentally new characteristics to strategic offensive arms of the United States. They had much more chances for making the first-strike attack. Besides, the ability of MIRV-type reentry vehicle to move warheads apart to great distances and with the specified time intervals increased greatly the probability of their getting over the nuclear ABM defense.

In the field of counteraction weapons the United States expanded antiballistic missile defense activities. In the 60s the ABM system Safeguard having antimissiles Spartan and Sprint equipped with nuclear warheads was being developed. It was specially designed for interception of ballistic missiles and their warheads.

This system was intended to be a combined territory and facility ABM system capable of protecting the whole territory of the country as well as providing additional protection of large cities and most important military facilities. New types of radar stations and electron systems for automated data processing and control were developed within the framework of Safeguard project. The ballistic target interception capabilities of this system surpassed those of AD nuclear means such as antiaircraft missile systems Nike Hercules and Bomarc.

Under these conditions the political leadership of the USSR took all possible measures to create the nuclear arsenal of adequate quality and quantity meaning to attain parity with the United States in the field of strategic offensive weapons. The nuclear arms race where the United States were the leader took on a broader character.

A real possibility for creating the system of nuclear antiballistic missile defense in the United States and a swift build-up of strategic offensive weapons predetermined the basic new military and technical problems facing the nuclear weapons centers of the USSR in the second half of the 60s. As for war equipment of strategic arms, these were first of all as follows:

- design of devices and nuclear weapons capable of withstanding a specific level of loads produced under injurious nuclear explosion effects (NEE) of ABM means;
- development of thermonuclear devices having a high specific yield for equipping multiple reentry vehicles designed for missile systems of strategic missile forces (SMF) and the Navy.

Some prerequisites to solution of these problems had been previously experimentally verified.

Application of new explosives having high specific properties promoted strengthening of device structures and reduction of their weights.

In the mid-60s VNIIEF worked out an efficient method of increasing the specific yield of thermonuclear devices. The specific yield increased almost two times as compared with the devices tested in 1961-1962.

This method of increasing release of the thermonuclear assembly energy was embodied in VNIIEF and VNIITF projects on devices of a new generation that were mainly designed for strategic missiles of SMF and the Navy.

In the second half of the 60s VNIIEF was concerned with prospecting research related to elaboration of conceptual approaches to design of devices having higher resistance to ABM means. For this purpose injurious nuclear explosion effects produced on a device structure and a nuclear warhead as a whole were studied. Calculations and engineering development efforts showed that it was essentially possible to create a super-strong warhead able to withstand a powerful set of injurious nuclear explosion effects at rather small distances from the antimissile explosion site but this would demand great weight expenditures.

Taking into account the proposed specifications of the future U.S. ABM interception means, the designs of warheads both super-strong and having higher resistance to ABM effects and providing moderate weight expenditures were studied and considered in the process of development.

Starting in 1967, VNIIEF was engaged in full-scale activities on development of third-generation thermonuclear devices. At this time the procedure of independent design of devices according to their weight categories still persisted, that is standardized device designs were made that could be at the same time used in carriers having different payloads and purposes. The "weight series" was undergoing a pronounced change towards lower device weight values. To equip strategic missiles with multiple reentry vehicles, VNIIEF was designing a thermonuclear device that was lighter than the previously made ones. VNIITF was also designing a thermonuclear device having the same weight and purpose. This was in fact a competitive development in this case.

Later, to exclude device development duplication, the Ministry leadership set limits to the device weight activities of both institutes.

VNIIEF was responsible for the higher weight category and VNIITF was concerned with lower weight devices. There were some isolated exceptions.

The experimental bases of both institutes were considerably improved and used for laboratory engineering development of the third-generation devices. New facilities were created including those used for laboratory studies into survivability of devices and nuclear warheads under effects produced by penetrating radiation, inertial, dynamic, temperature and climatic loads. Moreover, full-scale exposure experiments were made at the test sites to study radiation effects produced on device designs and firing automatics. These measures contributed into creation of the devices and nuclear warheads containing these devices that conformed to the tactical characteristics and specifications as well as operation requirements specified to them by the Ministry of Defense.

2.2. Problem of Antiballistic Missile Defense System Creation

2.2.1. Situation Before Entering Into the 1972 ABM Treaty. Problems of ABM System Creation

At the period preceding the ABM treaty the strategic alignment of the United States and Soviet Union forces was undergoing important changes.

The 60s were characterized by intensive development of ICBM in the Soviet Union as the means for delivery of NW that could directly hit the United States territory. At the period between 1967 and 1972 the total number of the USSR ICBM increased by more than two times and made up about 1550. The number of heavy ICBM also increased greatly and made up approximately 240. SMF became the main component of the Soviet Union strategic nuclear forces. At the same time, the nuclear submarine fleet potential was building up rapidly. The number of SLBM for these five years had increased more than five-fold and came to 500. In 1972 the total strategic nuclear and missile potential of the Soviet Union was about seven times as high as the minimum potential necessary to cause inadmissible damage to the United States in the first-strike attack (about 300 warheads were considered sufficient for practical destruction of the main part of the U.S. military and economic potential (MEP)).

The United States considered SMF of the Soviet Union as the main threat. This was explained by the fact that due to geopolitical features and general superiority of the Navy, NATO and the United States mainly monitored the World ocean and could expect to disable nuclear submarines of the Soviet Union even at the nuclear-free conflict stage.

The situation with development of SMF counteraction means was much more complicated. The United States considered two directions:

- making a forestalling nuclear attack on the Soviet Union ICBM launchers;
- creation of the ABM system capable of intercepting a great number of the Soviet Union ICBM warheads.

The first direction allowed for the possibility of a large-scale nuclear war because it was connected with a massive nuclear attack against the Soviet Union ICBM launchers, many of which were located rather close to the basic areas of the USSR life activities. A great difference in the number of strategic nuclear forces as compared with the Soviet Union was required for this direction implementation. In this case the following condition should be met within the framework of the simplest model:

$$g_1 N_1 \geq n_0^1 + \frac{1}{p_0^1}\left(N_2 - \frac{n_0^2}{g_2} \right), \tag{3.1}$$

where N_1 is the number of units in the strategic nuclear forces (STNF) of the first party delivering a forestalling nuclear attack on ICBM of the second party;

N_2 is the number of ICBM with the second party;

g_1, g_2 are the STNF launching reliabilities of both parties;

p_0^1 is the average probability of hitting the ICBM launcher with one unit of STNF of the first party;

n_0^1, n_0^2 are the minimum numbers of units of STNF (ICBM) with the first and second parties that are necessary to hit the MEP.

The hitting probability p_0^1 is a complex function that depends on the fortification level of ICBM launchers, the accuracy of STNF warheads, the energy release and the firing type.

Table 3.1 gives the values of the minimum required STNF number N_1 as a function of the number of ICBM N_2 and the efficiency p_0^1.

For simplicity sake we assume that $g_1 = g_2 = 0.8$; $n_0^1 = n_0^2 = 300$.

Table 3.1

N_2	500			1000			2000		
p_0^1	**0.2**	**0.5**	**0.8**	**0.2**	**0.5**	**0.8**	**0.2**	**0.5**	**0.8**
N_1	**1156**	**688**	**570**	**4281**	**1937**	**1351**	**10,531**	**4437**	**2914**

From table 3.1 it can be seen that the necessary level of N_1 value could be practicable only at high p_0^1 probability values. At $p_0^1 \leq 0.5$ there should be a great difference in N_1 as compared with N_2, and by the end of the 60s this difference started reducing rapidly as a consequence of the USSR nuclear and missile program development.

In addition, a great number of launchers N_2 and even high levels of $ð_0$ efficiency would require application of a large number of nuclear warheads. This raised the problem of a global radioactive injury in the course of such a conflict that would be caused by the levels of energy release necessary in the 60-70s. Therefore, the increase in strategic nuclear stores resulted in reduction of the possibilities for making a forestalling attack on the launchers and stabilization of the military and strategic situation.

The second direction presumed creation of a large-scale defense system including the means for a missile attack warning, some antimissile defense echelons equipped with nuclear and non-nuclear interception means. The following three problems to be solved with this system were discussed:

- preservation of the necessary response potential in case of a preventive enemy attack against STNF launchers;
- minimization of the damage in case of a massive enemy attack against the MEP;
- maintaining of their own preventive attack potential due to ABM system capability to intercept the main part of the warheads in the survived enemy STNF, which would make its reprisal inefficient and thus impossible.

A more restricted problem was also considered: a reliable interception of the limited number of warheads in case of their unauthorized launching (accident, terrorism, etc.).

As applied to the first problem, relation (3.1) is transformed within the simplest model of strategic nuclear arsenals into the following relation that defines the required ABM system efficiency level:

$$g_2 N_2 \geq n_0^2 + \frac{1}{p_0^2\left(1 - p_{\ddot{I}}^1\right)}\left(N_1 - \frac{n_0^1}{g_1}\right), \tag{3.2}$$

where $p_{\ddot{I}}^1$ is the average probability of ICBM warheads interception by ABM system of the first party.

For numerical illustrations we use the same g and n_0 values as given above. Table 3.2 shows the values of the minimum required STNF number N_2 as a function of the efficiency of hitting launchers p_0^2 and the efficiency of ABM systems $p_{\ddot{I}}^1$ that are given for three values of the number of launchers N_1.

From table 3.2 it can be seen that even at rather high values of the efficiency of hitting launchers p_0^2 (≈ 0.8), putting into operation of ABM system requires a great difference in the numbers of STNF N_2 and N_1 to make the first attack efficient.

This was the reasoning that served the basis for promoting ABM activities in the late 60s.

Table 3.2

N_1	**500**					
p_0^2	**0.5**			**0.8**		
$p_{\ddot{I}}^1$	**0**	**0.5**	**0/8**	**0**	**0.5**	**0.8**
N_2	**688**	**1000**	**1937**	**570**	**765**	**1351**
N_1	**1000**					
p_0^2	**0.5**			**0.8**		
$p_{\ddot{I}}^1$	**0**	**0.5**	**0.8**	**0**	**0.5**	**0.8**
N_2	**1937**	**3500**	**8187**	**1351**	**2328**	**5258**
N_1	**2000**					
p_0^2	**0.5**			**0.8**		
$p_{\ddot{I}}^1$	**0**	**0.5**	**0.8**	**0**	**0.5**	**0.8**
N_2	**4437**	**8500**	**20,688**	**2914**	**5453**	**13,070**

To solve the second problem, the number of the warheads having passed through ABM system should be no more than the level sufficient for causing inadmissible damage. In this case:

$$\left(1-p_{\ddot{I}}^{1}\right)g_{2}N_{2}\le n_{0}^{2} \tag{3.3}$$

To comply with this condition, table 3.3 given as an illustration shows the minimum required levels of the total ABM system efficiency $p_{\ddot{I}}^{1}$ as a function of ICBM number N_2 (for the used values g and n_0).

Table 3.3

N_2	500	1000	1500	2000	3000	5000
$p_{\ddot{I}}^{1}$	0.25	0.625	0.75	0.81	0.875	0.925

It is evident from these data that the requirements for the ABM system efficiency should be high but reasonable up to the number of ICBM N_2 ~ 1500-2000. Within the framework of this problem solution creation of ABM system had to be coordinated with restriction of the probable number of enemy warheads (for example, based on the appropriate bilateral Treaty).

Solution of the third problem reduces the difference between N_1 and N_2 values necessary to provide the possibility for delivering a preventive attack by the first party. In this case:

$$g_{1}N_{1}\ge n_{0}^{1}+\frac{1}{p_{0}^{1}}\left(N_{2}-\frac{n_{0}^{2}}{g_{2}\left(1-p_{\ddot{I}}^{1}\right)}\right) \tag{3.4}$$

Table 3.4 gives estimations of the minimum required STNF number N_1 as a function of ICBM number N_2, the efficiency of hitting launchers p_{0}^{1} and the ABM efficiency $p_{\ddot{I}}^{1}$.

As can be seen from table 3.4, the level of ABM system efficiency $p_{\ddot{I}}^{1} \approx 0.5$ is enough for the radical reduction of the number of STNF warheads N_1 necessary for the problem solution at $N_2 = 500$ and 1000; if $N_2 = 2000$, the required potential N_1 can be drastically reduced at $p_{\ddot{I}}^{1} = 0.8$.

Thus, under the late 60s situation conditions creation of a large-scale ABM system seemed to be rather promising in terms of the possibility for solution of all the problems under consideration.

Table 3.4

N_2	500								
p^1_0	0.2			0.5			0.8		
$p^1_{\ddot{I}}$	0	0.5	0.8	0	0.5	0.8	0	0.5	0.8
N_1	1156	375 *	375 *	688	375 *	375 *	570	375 *	375 *
N_2	1000								
p^1_0	0.2			0.5			0.8		
$p^1_{\ddot{I}}$	0	0.5	0.8	0	0.5	0.8	0	0.5	0.8
N_1	4281	1937	375 *	1937	1000	375 *	1351	765	375 *
N_2	2000								
p^1_0	0/2			0.5			0.8		
$p^1_{\ddot{I}}$	0	0.5	0.8	0	0.5	0.8	0	0.5	0.8
N_1	10,531	8187	1156	4437	3500	687	2914	2328	570

* a forestalling attack is not necessary because ABM system intercepts enemy warheads till the level of $< n^2_0$; N_1 value corresponds to the minimum required restraining level equal to n^1_0 / g .

One more challenging problem of the day should be mentioned that was related to material, technical and financial resources necessary for creation of a large-scale and rather efficient ABM system. This problem was in particular caused by the necessity of deploying antimissile systems in various regions for interception of the warheads moving towards different targets in separate directions. In this connection several new antimissiles with the suitable infrastructure had to be deployed for each new deployed ICBM. There arose the question of a competition between the enemy ICBM system build-up and ABM system development.

2.2.2. Appearance of MIRVs and Their Effects Upon ABM

In 1970 the United States put into service the first multiple independently-targetable reentry vehicles (MIRV) for their ICBM. In 1975 the same action was taken by the Soviet Union. By 1990 the main part of both the Soviet Union and the United States ICBM and SLBM war equipment consisted of MIRV. Table 3.5 gives the quantitative characteristics of this equipment based on the START-1 Treaty materials.

It is clear from table 3.5 that by 1990 ~ 88% of the total number of the Soviet ICBM and SLBM warheads was accounted for by MIRV; for the United States this figure was equal to 94.5%. The total numbers of MIRV with both countries were close to each other (~ 8000) at a close average number of MIRV per one ballistic missile (~ 6.5 MIRV). But there was a great asymmetry in MIRV distribution between land and sea-based STNF systems.

Table 3.5

	Characteristics	**USSR**		**U.S.**	
1.	**ICBM**				
	Number of ICBM and their warheads	**1398**	**6612**	**1000**	**2450**
	Number of ICBM with MIRV and their warheads	**744**	**5958**	**550**	**2000**
	Average number of warheads on ICBM	**4.73**		**2.45**	
	Average number of warheads on ICBM with MIRV	**8**		**3.64**	
2.	**SLBM**				
	Number of SLBM and their warheads	**940**	**2804**	**672**	**5760**
	Number of SLBM with MIRV and their warheads	**456**	**2320**	**672**	**5760**
	Average number of warheads on SLBM	**2.98**		**8.57**	
	Average number of warheads on SLBM with MIRV	**5.09**		**8.57**	
3.	**Total**				
	Number of ICBM and SLBM and their warheads	**2338**	**9416**	**1672**	**8210**
	Number of ICBM and SLBM with MIRV and their warheads	**1200**	**8278**	**1222**	**7760**
	Average number of warheads on ICBM and SLBM	**4.03**		**4.91**	
	Average number of warheads on ICBM and SLBM with MIRV	**6.9**		**6.35**	

Changing over to MIRV intensified the problem of the possibility for making a forestalling attack on enemy launchers. In the simplest opposition model for the two ICBM systems equipped with MIRV the condition for the possibility of delivering an effective attack against the enemy ICBM launchers has the following form:

$$g_1 N_1 K_1 \ge n_0^1 + \frac{1}{p_0}\left(N_2 - n_0^2 / g_2 K_2\right), \qquad (3.5)$$

where the symbols are the same as in relation (3.1), and K_1 and K_2 are the average numbers of MIRV on one ICBM for the first and the second parties.

Table 3.6 gives the values of the minimum required STNF number N_1 as a function of ICBM number N_2 and the efficiency p_0^1 for the same parameter values as in the estimations of table 3.1, but assuming that $K_1 = K_2 = 6.5$.

Table 3.6

N_2	**500**			**1000**			**2000**		
p_0^1	**0.2**	**0.5**	**0.8**	**0.2**	**0.5**	**0.8**	**0.2**	**0.5**	**0.8**
N_1	**483**	**228**	**164**	**964**	**420**	**284**	**1925**	**805**	**525**

In opposition of ICBM systems equipped with single warheads the increased number of ICBM resulted in possible blocking of conditions for carrying a preventive attack, while after changing over to MIRV such a possibility disappeared.

Based on table 3.1, it could be concluded that the offensive party had to have ~ 2 times as more ICBM missiles (with $p_0^1 \approx 0.5$ efficiency) to make the first-strike attack if the total number of enemy ICBM was 1000 and ICBM missiles were equipped with single warheads. After changing over to MIRV (K ~ 6.5), the number of ICBM smaller by a factor of 2.4 and the same efficiency p_0^1 were enough for delivering an effective attack by the offensive party. The number of ICBM necessary for the first-strike attack reduced by a factor of ~ 5.

These data illustrate a strategic instability caused by changing over to MIRV.

Under conditions of ICBM equipment with MIRV we consider the issue of probable effects produced by the deployed ABM system on preservation of the required reprisal potential in case of preventive enemy attack against ICBM launchers. Relation (3.2) true for single warhead equipment is transformed into:

$$g_2 K_2 N_2 \ge n_0^2 + \frac{1}{p_0\left(1 - p_{Ï}^1\right)}\left(N_1 - \frac{n_0^1}{g_1 K_1}\right) \qquad (3.6)$$

Table 3.7 shows the values of the minimum STNF number N_2 as a function of the efficiency of hitting launchers p_0^2 and the efficiency of ABM system $p_{Ï}^1$ given for various numbers of launchers N_1 (the numerical parameter values are similar to those above).

Table 3.7

N_1	500					
p_0^1	0.5			0.8		
$p_{Ï}^1$	0	0.5	0.8	0	0.5	0.8
N_2	228	398	968	164	270	589
N_1	1000					
p_0^1	0.5			0.8		
$p_{Ï}^1$	0	0.5	0.8	0	0.5	0.8
N_2	420	626	1869	284	510	1190
N_1	2000					
p_0^1	0.5			0.8		
$p_{Ï}^1$	0	0.5	0.8	0	0.5	0.8
N_2	805	1551	3792	525	991	2392

As compared with the data of table 3.2, the situation has changed fundamentally. With single warhead equipment, the number of targets N_1 = 1000-2000, the efficiency of hitting launchers p_0^2 = 0.5 and the ABM efficiency $p_{Ï}^1$ = 0.8

the number of ICBM had to be 8.2-10.3 times as great for a preventive attack . After changing over to MIRV, the number of ICBM under the same conditions had to be ~ 1.9 times as great. In case of the efficiency of hitting launchers p_0^2 = 0.8 and single warhead equipment the number of ICBM had to be 5.2-6.5 times as great and with MIRV the number of ICBM had to be increased only by a factor of ~ 1.2.

Thus, ABM system having single warheads could stabilize the situation by demanding a great excess in the number of ICBM necessary for making the first-strike attack, while with MIRV these stabilization capabilities almost disappeared. After changing over to MIRV equipment, reduction in the interception efficiency $p_{Ï}$ (other things being equal) was also an additional factor related to technical warhead interception capabilities.

The economic factor was for no benefit of ABM creation either. Under single-warhead equipment conditions several new antimissiles had to be deployed for each new enemy ICBM to maintain the required efficiency, while after changing over to MIRV each new ICBM demanded several tens of antimissiles.

Based on these combined arguments, it was admitted that with MIRV the deployed ABM was unable to stabilize the situation giving guarantees against the preventive attack on launchers.

Solution of the problem of preventing the possibility for the first-strike efficient attack on MEP using ABM proposes that the following condition should be met:

$$\left(1-p_{Ï}^{1}\right)g_2 N_2 K_2 \le n_0^2 . \tag{3.7}$$

To fulfil this condition, Table 3.8 gives the minimum required levels of the total ABM system efficiency $p_{Ï}^{1}$ as a function of the enemy ICBM number (K = 6.5).

The level of ABM system efficiency $p_{Ï}^{1}$ ≤ 0.8 is valid for a rather low enemy ICBM number $N_2 \le 300$ in the considered assumptions.

Table 3.8

N_2	100	200	300	500	1000
$p_{Ï}^{1}$, %	42.3	71.1	80.8	88.5	94.2

By the early 70s this level of the total ICBM number was exceeded greatly (by ~ 5 times) and in case of their equipment with MIRV creation of ABM system that could solve the problem under consideration seemed unreal.

To solve the third problem (an effective preventive attack by the first party provided it has ABM system) with ICBM equipped with MIRV, the following condition should be met:

$$g_1 K_1 N_1 \geq n_0^1 + \frac{1}{p_0^1}\left(N_2 - \frac{n_0^2}{g_2 K_2 \left(1 - p_{\text{Ï}}^1\right)} \right). \tag{3.8}$$

Table 3.9 gives estimations of the required minimum number of STNF N_1 as a function of ICBM number N_2, the efficiency of hitting launchers p_0^1 and ABM efficiency $p_{\text{Ï}}^1$. From the given data it follows that in the used assumptions deployment of ABM gives no significant gain in N_1 over the entire variation range of parameters under consideration N_2, p_0^1 and $p_{\text{Ï}}^1$.

Thus, changing over to MIRV made ABM system ineffective for solution of the third strategic problem too.

Table 3.9

N_2	500								
p_0^1	0.2			0.5			0.8		
$p_{\text{Ï}}^1$	0	0.5	0.8	0	0.5	0.8	0	0.5	0.8
N_1	483	427	261	228	206	139	164	150	90
N_2	1000								
p_0^1	0.2			0.5			0.8		
$p_{\text{Ï}}^1$	0	0.5	0.8	0	0.5	0.8	0	0.5	0.8
N_1	963	908	742	420	398	331	284	270	229
N_2	2000								
p_0^1	0.2			0.5			0.8		
$p_{\text{Ï}}^1$	0	0.5	0.8	0	0.5	0.8	0	0.5	0.8
N_1	1925	1870	1703	805	782	716	525	511	469

Let us sum up. Having a rather large number of ICBM (≥ 500) equipped with MIRV, almost equal parity conditions and a specific average number of MIRV on one ballistic missile ~ 6.5, the following can be concluded:

- deployment of ABM gives no guarantees against an effective preventive STNF enemy attack on launchers;
- deployment of ABM cannot protect one′s own MEP from the enemy nuclear attack;
- deployment of ABM prevents from delivering an effective preventive attack against the enemy.

These three “no” decided the ABM fate. Under conditions of opposition between the two superpowers the limited ABM capabilities were no longer of interest both for the Soviet Union and the United States. The parties agreed not to compete in this low-promising area and as a result the ABM Treaty was concluded in 1972.

In principle, there was no need of concluding this Treaty because ABM development in accordance with the aforesaid could make little contribution into the strategic balance of forces. Since the United States feared for the further speed up of programs related to creation of new Soviet ICBM, they could assume that their efforts in ABM area would only promote development of such a program being a form of compensation in this case. Together with the aforesaid this argument seemed to be the reason why the United States refused ABM creation. For the Soviet Union creation of ABM was accompanied with development of new technologies and significant extra expenditures for vague purposes. There was a simpler and effective way for the parity achieving and maintaining – build-up of ICBM system. And this was also enough for the Soviet ABM creation refusal.

2.3. MRVs and MIRVs for Strategic Missiles

The first MRVs and MIRVs for strategic missiles appeared in the United States.

Increase in the number of warheads on board the missile radically changed fighting and tactical capabilities of strategic arms and drastically increased the total number of warheads in SMS and the Navy.

As opposed to the single warhead, MIRV as a variety of war missile equipment enhanced greatly the fighting missile potential owing to the ability to hit several selective targets as well as its tactical capabilities to get over ABM attacking means.

Starting in the second half of the 60s, the activities in this area were placed on a broad footing.

The RV functional construction pattern experienced two fundamentally different development stages: first MRV without independent targeting were developed (known as dispensing-type vehicles) and later multiple independently targetable reentry vehicles (MIRV) were designed, which was analogous to the United States RV evolution from MRV to MIRV.

As opposed to the single warhead, the following principle was the basis of the dispensing-type vehicle. The MRV bus of the final missile stage was provided with several warheads covered with the common aerodynamic fairing that was released at the end of the active missile flight section. At the command of the missile control system the bus got detached and flew the ballistic trajectory. Over the target the warheads were separated with a special device and then each of them flew its own trajectory.

Clearly distribution of the missile payload from MRV among several warheads reduced weights and yields of the warheads.

At the same time, the fighting efficiency of several lower-yield devices in MRV was higher in terms of damage effects than that of the single warhead device.

On the other hand, under ABM counteraction conditions the number of antimissiles at least equal to the number of MRV warheads was required to hit all the MRV warheads, that is the ABM efficiency reduced noticeably due to the quantitative increase of the required interception means. These are general characteristics of the fundamental features of dispensing vehicles.

In 1967 the Soviet Army adopted for service RS-20 heavy liquid-propellant intercontinental missile with a single warhead that had been developed in the design bureau KB “Yuzhnoe” (Southern) and made at the Southern machine-building plant of Dnepropetrovsk city.

In November of the same year KB “Yuzhnoe” started designing dispensing-type vehicles for this missile. A powerful thermonuclear device designed by VNIIEF and tested before 1963 was chosen for this MRV.

Flight and design tests of RS-20 missile with MRV began in August of 1968. In accordance with the Resolution of the Government passed on October 20, 1970 ICBM RS-20 provided with the first Soviet dispensing vehicle was put into service.

As compared with dispensing vehicles, multiple independently-targetable reentry vehicles (MIRV) increased greatly the ICBM fighting efficiency both due to selective hitting of targets placed at a large distance apart and to tactical capabilities of MIRV under ABM counteraction conditions.

Fast progress made in improvement of the technology in all the areas related to strategic nuclear missile weapons resulted from implementation of MIRV programs.

In the mid-60s the military and industrial commission of the Soviet Union made a decision to arrange prospecting activities in organizations of the Ministry of General Machine Building and the Ministry of Defense. They were related to war equipment of RS-20 heavy two-stage liquid-propellant second-generation ICBM developed by KB “Yuzhnoe” including multiple independently-targetable reentry vehicles.

A large “throwweight” weight of this missile opened up wide possibilities for selection of the optimum MIRV make-up.

Various make-ups of war equipment were considered: from small-component MIRV having several high-yield warheads to many-component MIRV having thermonuclear devices being developed at that time by VNIIEF and VNIITF.

2.4. Third-Generation Nuclear Warheads in Nuclear Weapons Systems

The third-generation nuclear devices were developed first of all in the interests of war equipment for strategic missiles including those with MIRV. They were the basis for war equipment of nuclear arms of SMF and strategic missile systems of the Navy provided with single warhead missiles.

In particular, these charges found application:

- in ICBM: RS-10, RS-12, RS-14, RS-16, RS-18, RS-20 of various modifications;
- in SLBM: RSM-25 (2-nd and 3-d modifications), RSM-45, RSM-50.

At the same time, the third-generation devices were used as war equipment for other types of NW such as tactical missiles of the army, strategic cruise missiles (SCM), antisubmarine defense weapons based on submarines, surface ships (ASD weapons on SM/SS) and torpedoes of the Navy.

At that period of time some negative phenomena started emerging during development and deployment of nuclear arms in the Soviet Union – creation of too many types of carriers and, respectively, expansion of the nuclear weapons range as a result of various requirements for the war equipment.

The history governed aspiration for regular improvement of weapons provided the basis for increasing the number of types of NW systems. However, this process was taking place under the following conditions:

- the absence of the required conceptual stage for development of NW systems whereat the technical weapon appearance is defined. NW systems (models) were very often developed in response to the United States analogs;
- sometimes insufficient scope of pre-design research of weapons systems;
- the lack of the required coordination during NW development, mainly at the complex level, etc.

As for other types of the Armed Forces and branches, the following should be noted. The fact that the customer wished to equip with nuclear devices the weapons systems that were developed mainly for combat actions in ordinary military operations, that is using high explosives, also contributed into nuclear warhead range expansion in addition to the above reasons. A large number of conventional weapons were in operation and under development (torpedoes, projectiles, cruise missiles, etc.); however, an additional arsenal of the same nuclear munitions appeared to execute a wide range of specific operational missions.

Appearance of the similar-purpose weapons systems was also explained by the fact that various influential groups from the USSR military and industrial complex administration rendered strong support to design bureaus, which in practice often resulted in the following situation: there were as many types of weapons systems as there were design bureaus.

In the 80s some attempts were made to put the NW range in good order, for which purpose a more thorough conceptual development of the weapons systems was used, coordination of developments was improved, comprehensive special-purpose programs were drawn up, etc. But all these activities were performed on the eve of concluding the treaties with the United States on limitation and reduction of nuclear armaments.

2.5. Development of Thermonuclear Weapons for Equipment of Strategic ICBM and SLBM of the Latest Generation

In the second half of the 70s, after the programs aimed at development of ICBM and SLBM including those with MIRV had been implemented, the Soviet Union approached the strategic nuclear potential of the United States in the number of strategic offensive arms and warheads.

On June 18, 1979 SALT-2 Treaty was signed in Vienna that provided for limitations on all components of strategic offensive arms. The total number of strategic carriers was restricted to 2400 units and starting on January 1, 1981 it was restricted to the level of 2250. The restricted number of ICBM and SLBM with MIRV was at the level of 1200 units including ICBM with MIRV restricted to 820 units.

In the second half of the 70s the United States began a full-scale development of ICBM (ÌÕ) and SLBM (Trident system) of a new generation. Research and development efforts related to them had been started even in the early 70s.

The conceptual basis for these projects, that is a “force opposing pressure” set ICBM ÌÕ and SLBM Trident the task to hit highly fortified facilities of ICBM silo launchers type and fighting control posts. This was a new attempt made in the course of the cold war to achieve superiority in nuclear arms due to qualitative improvement of the nuclear missile technology. The Soviet Union immediately took adequate response measures.

The defense industries as well as both nuclear centers were involved in development of new highly efficient thermonuclear devices and warheads to equip new advanced:

- ICBM RS-22 and
- SLBM RSM-52.

On August 6, 1975 the Government passed the Resolution according to which the Ministry of Medium Machine Building (MMMB), the Ministry of General

Machine Building (MGMB) and the Ministry of Defense (MOD) were charged to make research and search efforts to increase greatly the aiming precision of advanced Navy strategic missile systems. To this end, submarine location and course determination mistakes were to be considered and new missile control principles were to be used. These efforts were also aimed at creating a small-sized WH having appropriate tactical characteristics and specifications.

According to this resolution, the scientific and technical leadership of VNIIEF and VNIITF were charged to prepare proposals on creation of a thermonuclear device for an advanced small-sized WH to be used in MIRV of SLBM of RSM-52 type.

Some time earlier there had been a meeting of the scientific and technical council of MMMB devoted to the results of preliminary study into WH for RSM-52 missile. The meeting noted unsatisfactory proportion in warhead designs between their total weights and the weight of special content.

Design parameters of W76 warhead for Trident system that were taken from the published materials made it possible to estimate the assumed specific yield of WH. It was much higher than the specific yield of the similar domestic WH being used in SLBM at that time.

The borderline that development engineers had to overcome while improving specifications of WH for sea-based ballistic missiles was very high.

The problem consisting of the following two indissolubly united parts had to be solved: creation of a cone-shaped high-velocity warhead having perfect aeroballistic characteristics and a thermonuclear device having a high specific yield.

Twenty four years after creation of the first RV for the intercontinental missile the first WH project was jointly developed, dimension and weight characteristics of the device, war equipment automatics as a whole and RV as an operational missile stage were optimized. Aeroballistic characteristics of the warhead, its weight, dimensions, center-of-gravity location as well as the appropriate parameters of the proposed not yet tested device and firing automatics system were mutually coordinated.

At the same time, VNIIEF and VNIITF began designing thermonuclear devices and the firing automatics system, keeping in mind those limitations that were specified by the WH body parameters.

To fulfil this task, VNIIEF worked out design approaches to several small-sized initial atomic device versions.

In 1976-1983 VNIIEF carried out 33 proving ground tests within the project of creating a small-sized device for SLBM RSM - 52. Numerous proving ground tests were caused by a great number of device versions under development and partly by test failures. Besides, the computational center had too little capabilities compared with the scope of activities.

As for development of WH for SLBM RSM-52, VNIIEF also took measures to miniaturize firing automatics systems. On this way it succeeded in achieving good results: the weight and dimension parameters of the firing automatics system improved radically as compared with those of previous generations.

Concurrent and competitive intense activities aimed at creating a thermonuclear device for RSM-52 missile were carried out in VNIITF that also was engaged in designing several versions of devices including with VNIIEF-produced thermonuclear device module having been successfully tested in 1977.

In the long run, creation of the WH for RSM-52 missile took the form of two stages.

Since the date of adopting the system with SLBM RSM-52 for service was expiring, in the early 80s VNIITF completed development of the WH with one of the device versions based on VNIIEF thermonuclear module. The missile system with SLBM RSM-52 equipped with these warheads started deploying in 1983.

To achieve the desired WH specifications, both institutes proceeded with their activities. As a consequence, VNIITF made a thermonuclear device having the required parameters. The warhead with this device whose development was completed in 1985 had characteristics that were much higher than those of its predecessor and complied with the tactical requirements and specifications.

In 1987 this warhead was put into service of the missile system with SLBM RSM-52.

On June 23, 1976 the Government′s Resolution was passed. According to this resolution, KB “Yuzhnoe” and the Southern machine-building plant were charged with making a new three-stage solid-fuel ICBM RS-22 missile whose basic specifications were to be close to those of the U.S. ICBM MX. RS-22 missile railroad and silo basing was provided for.

Development of the device for ICBM RS-22 MIRV war equipment had a complicated, contradictory and even sometimes conflicting character. This was due to the difficulties KB “Yuzhnoe” faced while making the first solid-fuel ICBM and because of the customer′s requirements.

By that time VNIIEF had created a new rather light small-sized atomic initiator. Its first test took place in 1978.

According to the directive documents issued by the Commission of the Presidium of the USSR Council of Ministers on military and industrial issues and the Ministry of Defense that committed the MMMB to develop war equipment for RS-22, VNIIEF designed a thermonuclear device that was successfully tested in 1979.

In January of 1982 the joint meeting of the scientific and technical leadership of KB “Yuzhnoe” and VNIIEF was arranged. It took the decision to improve RS-20 device arrangement parameters and to reduce the WH weight due to combined device and WH body optimization and reduction of the automatics system weight while providing the required warhead middle limitation.

VNIIEF made the device with a narrow middle and tested it successfully in 1984. Development of the device meeting new weight and dimension limitations demanded great efforts and creativity from the institute specialists.

ICBM RS-22 having improved tactical characteristics and specifications and equipped with MIRV provided with 10 WHs entered service in 1989. It was deployed in silo launchers.

Chapter 5

Soviet Program of Nuclear Explosions for Peaceful Purposes

Contents

Introduction

The idea of technical (national economic and scientific) application of nuclear explosions originated as soon as the mankind obtained a new powerful source of energy and nuclear particles. It is interesting to remember that the report of the Soviet Information Bureau on the first application of nuclear weapons in the Soviet Union informed of its use for irrigation purposes. Hardly had almost a year passed since the first Soviet atomic test took place on August 29, 1949, when I.V.Stalin signed a special Resolution of the USSR Council of Ministers on May 16, 1950. It was entitled "On scientific-research, design and experimental efforts on applying atomic energy for peaceful purposes". It included the following part as an independent task (to be fulfilled during 1950): "Study into the possibility of applying atomic energy for explosion operations. Calculation and theoretical studies into characteristics of underground atomic explosions and preliminary technical and economic estimation of probable atomic explosion application methods". In this document Yu.B.Khariton and D.A.Franck-Kamenetsky were indicated as the principal investigators of this task. The results generated from tests of the first Soviet nuclear devices allowed the scientists to conclude on the possibility for efficient application of the nuclear explosion energy for national economic purposes.

In the early 1950s G.N.Flerov and D.A.Franck-Kamenetsky working in Arzamas-16 at that time suggested that the underground nuclear explosion should be used for build-up of one of the uranium (uranium-233) isotopes and the explosion site with the heated rock should be applied as the heat reservoir. To put it differently, they expressed the idea of creating an artificial deposit of the specific useful product using an underground nuclear explosion. The heated explosion area was considered a geothermal source variety. In late 1954 D.A.Franck-Kamenetsky and Yu.A.Trutnev made detailed calculations of G.M.Flerov′s and D.A.Franck-Kamenetsky′s proposal on applying the energy and neutrons of under ground exploded hydrogen bombs for peaceful purposes. In the spirit of those times this proposal as well as other proposals that followed and were related to application of nuclear explosions for peaceful purposes were classified as top secret.

Flight of thought in such an unexpected area was given an unusual swing and in parallel with pragmatic ideas there were by far extravagant proposals. Imparting to space vehicles of giant velocities to reach far universes was among them. It was proposed to arrange small nuclear explosions to be made periodically at a certain distance from the “explosion vehicle”. Nuclear explosions governing weather were no less eccentric.

This was the period of intensive search and hopes when the atomic nucleus energy seemed to be fully dependent on a human being and negative side effects of its application could be taken under a guaranteed control.

The first underground nuclear explosions were carried out in the United States in the late 50s-early 60s and then in the Soviet Union. They gave abundant information and revealed the basic regularities characteristic of such experiments. The ideas of industrial application of nuclear explosions acquired a well-reasoned scientific and technical basis.

The U.S. Plowshare Program on practical implementation of nuclear explosions for peaceful purposes was started in 1957. This program provided for such activities as theoretical and experimental studies of the phenomena accompanying nuclear explosions; development and testing of special nuclear devices for scientific and industrial purposes; studies of the areas for probable application of nuclear explosions for peaceful purposes; substantiation and implementation of the projects using nuclear and explosive technologies for peaceful purposes. An impressive program was worked out according to which nuclear explosions could be used for extracting mineral resources, intensification of oil extraction, construction of large structures such as dikes, dams, maritime canals and harbors, for making artificial water storage basins, production of heat and electric energy from the energy of underground nuclear explosions. Manufacture of valuable mineral components (graphite diamonds) for scientific purposes, studies of the Earth structure, production of transplutonium elements were also proposed.

The program of peaceful nuclear explosions in the Soviet Union was in many respects based on the ideas and results of the American program though the Soviet program was more extensive in terms of its practical implementation. The Soviet Union conducted 124 peaceful nuclear explosions, 36 tests were carried out to provide complete development of industrial nuclear devices while the United States made 27 peaceful experiments and tests for engineering development of industrial nuclear devices.

In August of 1963 the Moscow treaty was concluded that put an end to nuclear explosions in the atmosphere, under water and outer space. Creative ideas of nuclear physicists and later of specialists in many other fields who showed an interest for peaceful application of nuclear charges were concentrated purely on underground nuclear explosions.

A large scope of construction activities in the Soviet Union in the 50-70s, development of the biggest deposits on vast sparsely populated territories, unsurpassed experience gained in large-scale chemical HE explosions created wide prerequisites for successful application of underground nuclear explosions for industrial purposes in our country.

One cannot but note two important events that took place in the USSR and in the United States in 1966 and were directly connected with the issue under discussion.

In the first half of 1966 the deputy chairman of the Council of Ministers of the USSR and the chairman of the State science and engineering committee V.A.Kirillin asked some leading physicists of the country including V.L.Ginzburg, B.M.Pontekorvo, Ya.B.Zeldovich, A.D.Sakharov and others to write reviews describing their vision of the future physics development opportunities in the coming decades. These review materials were prepared and in May 1966 they were published in the form of a separate typewritten booklet to be used only for official purposes. It was entitled “Science of the future. Some predictions of the science development perspectives”.

The booklet consisted of about 50 pages and only 50 copies were made. A.D.Sakharov was the author of the concluding article in this booklet.

In his “Reminiscences” Andrei Dmitrievich noted: “...I was working with great enthusiasm and wrote a short article with a long flight of fancy. Concentrating again on general questions of the mankind fate, I can say that the work at this article had a great psychological importance for me”. Later some statements from this article entered “Meditation on the progress...” (1968) and the article “The world in half a century” (1974) .In his article A.D.Sakhsrov gave much consideration to future opportunities for peaceful application of underground nuclear explosions.

A.D.Sakharov was full of optimism and believed that many peaceful projects would become a reality. He even deviated from the theme of underground nuclear explosions and put in the list chamber explosions in the interests of meteorology and their application as the explosion vehicle acceleration means. Moreover, twenty years later, in October of 1988, he published the proposal to use superpowerful underground thermonuclear explosions (about 100 Mt) to prevent probable catastrophic earthquakes and relieve dangerous critical stresses in the earth′s crust. This proposal was equally fantastic and disputable for some reasons.

In 1966, when the booklet “Science of the future” with A.D.Sakharov′s article appeared in the Soviet Union, the competent specialists and Edward Teller among them delivered 16 lectures at the Stanford University that were devoted to industrial application of underground nuclear explosions. They gave an impressive idea of probable applications of nuclear charges. The project of creating a new canal through the Isthmus of Panama using nuclear explosions seemed extremely promising to the Americans. According to the law passed by the Congress, President of the U.S.

approved a special commission to carry out research and allotted 17.5 million dollars. The estimations showed that the new canal could be built in 10-14 years and would be ready even by 1977-1981. This required from 750 to 1440 million dollars. The total number of nuclear explosions depending on the chosen yield should range within 200-300.

Underground nuclear explosions were considered by the American specialists as a very effective method for building harbors, water storage basins and open cuts, canals, pits, dams, tanks for carrying off the water in case of floods, reservoirs for disposal of heavily contaminated wastes, for crushing shale and intensification of oil and gas extraction and even for building artificial ponds in recreation areas.

Considering perspectives for applying nuclear explosions for scientific purposes, E.Teller pointed out in his lecture that they were particularly efficient for neutron and nuclear-physical experiments and creation of new elements, for neutrino physics and study of the Earth structure using seismic waves induced by a nuclear explosion. It was an ideal source of such waves.

Thus, by 1966 perspectives for peaceful application of underground nuclear explosions seemed highly promising both to Soviet and to American specialists. It is no mere chance that one of the central clauses in the nuclear nonproliferation Treaty approved by the United Nations Organization in 1968 and brought into force on March 5, 1970 ran as follows: “Each Member of the present Treaty commits itself to take appropriate measures to ensure that all potential benefits from any peaceful application of nuclear explosions will be available on a non-discrimination basis to the present Treaty member countries having no nuclear weapons. This should be done according to the present Treaty, under appropriate international supervision and using appropriate international procedures. The cost of the explosive devices used by these Treaty Members should be as low as possible and should include no expenditures for their study and improvement...”

From this point on talking about “potential benefits” of peaceful application of nuclear explosions was a peculiar sign of a good form in discourses of the world country leaders and in speeches of authoritative scientists made at international forums.

At the same period of time, in 1969-1971, the Soviet-American negotiations took place where the experts in peaceful application of underground nuclear explosions participated. In addition to purely technical aspects, this was the event that symbolized certain confidence at that time.

All nuclear explosion displays were considered as useful factors:

- mechanical – rock outburst, breaking, heaving followed by formation of cavities, effects on meteorites and comets, application of seismic effects;

- nuclear-physical – isotope fusion and measurements of nuclear-physical constants;
- thermal – steam generation; combustion of harmful agents;
- electromagnetic – shaping of radio pulses and application of the magnetodynamic effect (accelerators), thermonuclear current generators.

About 50 various technical proposals for application of nuclear explosions were made.

1. Concept of Peaceful Nuclear Explosions

The following statements were made the basis for the program and projects of peaceful nuclear explosions (not at the same time but as the matter came to be better understood):

1. The explosion (program) result cannot be achieved using other existing means or the NE effect is attained with the costs and expenditures of resources several times less than in the alternative non-nuclear method, that is with a high cost effectiveness.
2. There should be no significant harmful side effects upon the personnel, population and the environment.
3. Selection of the explosive device, the explosion site and conditions should ensure minimum possible contamination of the environment, of entrails of the earth, in particular.
4. When making explosions, the provisions of the Moscow Treaty Banning Nuclear Weapons Tests in the Atmosphere, Outer Space and under Water (August 5, 1963) and the Peaceful Nuclear Explosions Treaty (May 25, 1976) between the Soviet Union and the United States should not be violated.
5. Development of nuclear explosive technologies should be oriented towards achieving high economic effects.

The ideas of applying underground nuclear explosions for national economic purposes found their practical implementation in the Soviet Union owing to the initiative and great support rendered by the former Minister of medium machine-building Ye.P.Slavsky. He directly participated in the first peaceful underground nuclear explosion on January 15, 1965 that was made to create a water storage basin in the Chagan river-bed of Semipalatinsk test site.

In November of 1965 the meeting of the leading scientists, chief designers of nuclear weapons in our country where A.D.Sakharov, Ye.I.Zababakhin took part considered future opportunities for efficient application of peaceful nuclear explosions. The meeting participants, academician A.D.Sakharov among them, showed their sincere desire to promote successful peaceful application of explosions and to use all the knowledge they had to create nuclear devices providing maximum efficiency of their application in the national economy. At this meeting the following requirements were specified for industrial nuclear devices:

- minimum residual radioactivity after explosion for the least possible contamination of the atmosphere, rocks and underground water;
- maximum agreement between the estimated and actual nuclear device yields to achieve the preset aims;
- optimum nuclear device overall dimensions and form conforming to the conditions of its descent into deep boreholes.

Special nuclear devices for peaceful explosions were developed and made on short notice. These devices had overall dimensions that made it possible to use them in standard cased boreholes. They withstood high pressures and temperatures and had the project specified energy release levels.

A large scientific potential in the new field had been gained for a few years. Physical and mathematical models of the phenomena accompanying explosions were developed which allowed switchover to calculations on computers. This defined technical scope and high efficiency for applying underground nuclear explosions to implement many national economic programs whose fulfilling with conventional means was not very efficient. At the same period of time the basic provisions of the domestic Program for applying peaceful underground nuclear explosions (Program 7) were elaborated. Professor A.D.Zakharenkov was appointed the head of this Program, professor O.L.Kedrovsky was its scientific supervisor. This Program provided for:

- studies into the basic processes proceeding in various environments of underground nuclear explosions and explosion accompanying effects;
- study of helpful effects to create various types of nuclear-explosive technologies;
- development and experimental-industrial verification of nuclear-explosive technologies; safety estimation of nuclear explosive technologies;
- cost estimation of structures and products created with nuclear explosions.

The main feature of this program was its interindustry character. Few examples can be given when more than ten union ministries such as the Ministry of Medium Machine Building, Mingazprom, Minnefteprom, Minugolprom, Minenergo, Mintsvetmet, Minvodkhoz, etc would be involved in program implementation and to whose orders peaceful nuclear explosions would be conducted.

The principal scientific-research teams participating in these activities were as follows. VNIIEF (Arzamas-16) and VNIITF (Chelyabinsk-70) were developing nuclear devices and means for their blasting. The design bureau ATO (Moscow) was working out reusable delivery and blasting means. All-Russian Scientific Research and Design Institute of Industrial Technology (the former PromNIIproject) in close cooperation with the Special sector of the Geophysics Institute of the USSR Academy of Sciences, V.G.Khlopin Radium Institute, the Biophysics Institute of the USSR Ministry of Public Health, the Institute of Applied Geophysics of the USSR of Goskomgidromet, many specialized technological institutes and production organizations (more than 150 institutes and organizations) carried out a large scope of studies into effects and processes involved in a nuclear explosion. They created fundamentals of program studies and developments for applying various technological effects of underground nuclear explosions.

From all the areas under the following three technologies were of great significance:

- deep seismic sounding (DSS);
- construction of underground reservoirs;
- intensification of oil and gas extraction.

For these purposes camouflet nuclear explosions were mainly used.

2. Classification of Peaceful Nuclear Explosions Conducted on the Territory of the Soviet Union

A large-scale program of applying nuclear explosions in the interests of the national economy was implemented in the Soviet Union in 1965 through 1988. In annex 1 Minatom of Russia gives official summarized data on peaceful nuclear explosions.

Within the program of peaceful nuclear explosions (industrial explosions - IE) the Soviet Union made 124 nuclear explosions. 116 of them were explosions of individual nuclear devices and 8 were multiple peaceful nuclear explosions. 19 nuclear devices were exploded as parts of 8 multiple nuclear explosions. Thus, the total number of peaceful NE was 135.

Table 5.1 shows distribution of industrial explosions and nuclear devices used for them from year to year.

Table 5.1

Year	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1987	1988	Total
N_{IE}	4	2	1	4	4	3	8	8	5	6	3	3	7	9	9	5	5	8	9	11	2	6	2	124
N_{NC}^{IE}	5	2	1	6	4	3	10	8	5	6	3	3	7	10	13	5	5	8	9	12	2	6	2	135

Industrial explosions were started at Semipalatinsk test site in 1965 when excavating explosions were made to produce craters for artificial water storage basins. The record number of peaceful explosions was made in 1984 - 11, in 1971, 1979, 1983 8-9 explosions were conducted each year.

It can be seen from table 5.1 that application of nuclear explosions for industrial purposes was rather active in 1965-1988, that is during almost the entire period of underground nuclear tests in the Soviet Union.

For engineering development of industrial nuclear devices and making industrial explosions 156 nuclear tests were conducted from the total number of 494 nuclear tests (or ~31.5%) and 173 nuclear devices were exploded from the total number of 748 nuclear devices exploded during this period of time (or ~ 23%).

The region distribution of industrial explosions and explosions of nuclear devices is shown in table 5.2.

Table 5.2

Region	N_{IE}	N_{NC}^{IE}
1. European part of the RSFSR	48	52
2. Asian part of the RSFSR	32	32
3. Kazakhh Soviet Socialist Republic	39(32)	46(37)
4. Ukrainian Soviet Socialist Republic	2	2
5. Uzbek SSR	2	2
6. Turkmen SSR	1	1
Total	124	135

For Kazakhhstan N_{IE} è N_{NC}^{IE} are given in parentheses for the territory beyond Semipalatinsk test site. There were no industrial explosions at Novaya Zemlya test site.

The greatest number of industrial explosions (80) were made on the territory of the Russian Federation.

From 135 explosions of nuclear devices 130 were borehole explosions, 4 explosions were arranged in tunnels and 1 explosion was made in a shaft.

The total energy release of all industrial explosions was about 1.78 Mt.

36 types of nuclear devices were used for industrial explosions within the program. Some types of nuclear devices were used repeatedly (one type of nuclear devices was used 55 times to implement the program of industrial explosions).

From 135 explosions of nuclear devices 53 of them fell on nuclear devices developed by VNIITF and in 82 explosions VNIIEF developed devices were used. From 36 types of nuclear devices used for industrial explosions 24 of them were developed by VNIIEF and 12 types were designed by VNIITF including the nuclear device that was most often used for explosions.

It should be mentioned that not all the nuclear devices developed within the program of complete development of industrial nuclear devices were used for industrial explosions. In some cases the nuclear devices previously made for other (military) purposes were applied for industrial explosions.

For engineering development of industrial nuclear devices the USSR conducted 32 nuclear tests. 26 of them were independent nuclear tests and in 6 of them two nuclear devices in each were tested. In these 6 multiple nuclear tests 9 nuclear devices were tested in the interests of engineering development of industrial nuclear devices. The remaining 3 nuclear devices were tested for different purposes. Besides, 3 additional tests in 3 multiple nuclear tests whose main objective was different were carried out within the program of engineering development of industrial nuclear devices. Thus, the entire program of engineering development of industrial nuclear devices in the Soviet Union included 38 tests of nuclear devices that consisted of 26 independent and 9 multiple nuclear tests.

Table 5.3 shows the year distribution of nuclear tests and explosions of nuclear devices in the interests of engineering development of industrial nuclear devices.

From table 5.3 it can be seen that the main portion of activities aimed at engineering development of industrial nuclear devices fell on 1966-1970 when ~ 70% of the total amount of industrial nuclear devices were completely developed under full-scale conditions for 5 years.

Table 5.3

Year	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**	**1971**	**1972**	**1973**	**1974**	**1975**	**1983**	**1984**	**Total**
N_{NT}	2	2	7	4	3	5	4	1	1	1	1	1	-	-	32
N_{NC}	2	2	7	6	3	6	4	1	2	1	1	1	1	1	38

23 types of various industrial nuclear devices were tested within this program. The maximum number of tests that were carried out for one type of nuclear devices was 5.

Within the programs of engineering development of industrial nuclear devices 36 tests of nuclear devices from 38 were conducted at Semipalatinsk test site and 2 tests of nuclear devices were performed at Novaya Zemlya test site. From 38 explosions of nuclear devices made for engineering development of industrial nuclear devices 32 of them were arranged in tunnels and 6 explosions were made in boreholes. This points to the fact that tests in tunnels were the determining type of engineering development of industrial nuclear devices. The total energy release of 38 explosions made for complete development of industrial nuclear devices was ~ 900 kt.

When implementing the program of engineering development of industrial nuclear devices, VNIIEF tested 9 types of nuclear devices in 15 nuclear tests and VNIITF tested 14 types of nuclear devices in 23 nuclear tests.

VNIIEF and VNIITF specialists also developed and tested special thermonuclear devices that had a very small portion of energy release due to fission reactions.

VNIITF made a wide range of nuclear explosive devices 182 mm and 260 mm in diameter. They were capable of operating at 120°Ñ and pressures as high as 750 atm. Designs and physical layouts of these munitions allowed standard drilling equipment to be used and long-term ecological safety to be ensured.

Annex 1 classifies peaceful explosions according to their application, explosion depth, energy release. It also gives the data on the state of facilities, radiation situation in 1994 and lists the ministers in whose interests these explosions were made.

From the data of the classification diagram (table 5.4) it is evident that the most explosions were arranged according to the deep seismic sounding program (39). Creation of experimental-industrial reservoirs (25) and intensification of oil and gas extraction (21) were the second and complete development of the technologies for making cavities in rock salt masses was the third (17).

The majority of explosions (84) were made at the depth of up to 1000 m, the remaining explosions (40) were conducted at 1000-2500 m depths.

Table 5.4 shows distribution of the number of peaceful explosions with their specific purposes. It is seen that the main part of technological explosions had the status of experimental-industrial studies, that is they were aimed at generating practically important results.

Table 5.4

Industrial underground explosions of nuclear devices made on the USSR territory in 1965-1988. Classification according to their specific purposes

Specific purpose (customer)	Conventional name of the technological site (number of peaceful nuclear explosions)	Total
Experimental-industrial activities using nuclear-explosive technologies		
Deep seismic sounding of the earth′s crust in search of the structures promising for exploration of mineral resources (USSR Ministry of Geology)	**"Agat", "Batolit"(2), Globus (4), Gorizont (4), "Quartz" (3), Kimberlit (3), Kraton (4), Meridian (3), Meteorit (4), Region (5), Rift (3), "Rubin" (2), "Shpat"**	**39**
Creation of experimental-industrial underground reservoirs (USSR Ministry of Gas Industry)	**Vega (15), "Dedurovka" (2), Lira (6), "Sovkhoznoe", "Tavda"**	**25**
Intensification of oil extraction (USSR Ministries of Oil Industry and Geology) and intensification of gas discharges (USSR Ministry of Gas Industry)	**Angara, Benzol, "Butane" (4), Vyatka, Helium (5), Grifon (2), Neva (4), Oka, "Takhta-Kugultinskoe", Sheksna**	**21**
Shutoff of gas flowing wells (USSR Ministry of Geology)	**"Krater", "Pamuk", "Pirit", "Fakel", "Urta-Bulak"**	**5**
Ore breaking (USSR Ministry for Production of Mineral Fertilizers)	**Dnepr (2)**	**2**
Disposal of biologically dangerous industrial effluents of petrochemical production plants into deep geological formations (USSR Ministry of Oil Refining and Petrochemical Industry)	**"Kama" (2)**	**2**
Prevention of coal dust and methane blowing (USSR Ministry of Coal Industry)	**Klivazh**	**1**
Creation of dams-tailing storage facilities by rock loosening (USSR Ministry of Non-Ferrous Metallurgy)	**"Kristall"**	**1**
Creation of ditches in alluvial soils (USSR Ministry of Melioration and Water Handling Facilities)	**Taiga**	**1**
Experimental activities aimed at complete development of nuclear-explosive technologies for industrial purposes **Principal investigator – USSR Ministry of Medium Machine-Building**		
Creation of underground reservoirs in rock salt masses (Kazakhhstan, Gurievskaya region, about 20 km from Bolshoi Azgir settlement)	**"Halite" (17)**	**17**
Creation of water storage basins (Semipalatinsk test site of the USSR Ministry of Defense)	**"Sary-Uzen", "Telkem" (2), "Chagan"**	**4**
Complete development of the technique for making craters for water storage basins and study of engineering seismology problems	**"Sais-Utes" (3)**	**3**
Complete development of the technique for disposal of radioactive explosion products	**Semipalatinsk Test Site (STS) (2)**	**2**
Discharge of soil over mountain flanks for dam making (Semipalatinsk test site of the USSR Ministry of Defense)	**"Lazurit"**	**1**
Total		**124**

3. Technical Application of Underground Nuclear Explosions

3.1. Deep Seismic Sounding of the Earth′s Crust

Deep seismic sounding (DSS) using nuclear explosions as a seismic source has become an advanced way of studying the depth earth′s crust structure. This method is based on application of a high-power seismic signal reflected from the associated beds of the earth′s crust. The recording range of the signal produced by a nuclear explosion may be as great as 700 km, while that of a conventional explosion using chemical explosive is no more than 20 km. A fundamentally new method of geophysical exploration is intended to speed up detection of promising regions containing oil, gas and other mineral resources. In 1965 the Ministry of Geology and the Ministry of Medium Machine Building started experimental and methodical studies to develop the technique for recording seismic waves induced by underground nuclear explosions. When making peaceful nuclear explosions in Urta-Bulak, Pamuk, Takhta-Kugulta, Sovkhoznoe gas fields and in Osinskoe oil deposit, seismic signals were recorded at various distances from the explosion site.

As a result of studies in 1966-1970, some methodical matters were settled, the data on the depth structure of some regions were generated, instrumentation was completed and some organization problems were solved.

The developed technique made it possible in a rather short period of time to arrange regional reconnaissance operations whose performing using a conventional deep seismic sounding technique would have taken many years and much more labor efforts.

The seismic sounding technique consisted in the following. The nuclear device (the source of elastic vibrations) was placed in a specially predrilled borehole 500-1000 m deep. Seismic recording instruments actuated with a radio signal were arranged over the line with helicopters. The length of the lines for sounding ranged within 1.5-4 thousand kilometers. The number of explosion sites on the line was 3-5 and the distance between them ranged within 500-900 km.

The main technological and methodical DSS technology requirements were as follows:

- necessity of making an explosion at a strictly specified time because the stations started recording in response to the radio signal and the time of seismic station operation was very limited;

- compliance with the prescribed explosion yield, which was necessary for interpretation of the generated results;
- observance of the radiation safety regulations.

The radiation safety was provided by correct selection of geological and hydrological explosion conditions, the explosion depth and energy, the optimum borehole structure and thorough insulation operations during its drilling. There were almost no negative seismic effects because the operations were performed in thinly populated districts and arrangement of explosion sites could be rather widely varied by locating them far from the populated areas.

A great benefit of the deep seismic sounding technology is its lower cost as compared with conventional methods and the possibility for study the structure of lengthy lines at a great depth and in a short space of time.

In 1971-1988 39 underground nuclear explosions were made on 14 DSS lines having a total length of 70,000 km. This was done within the comprehensive program of the USSR Ministry of Geology and the USSR Academy of Sciences that was aimed at studying the geological earth′s crust structure. Besides, 2 DSS lines were made using incidentally industrial nuclear explosions made at that time for different purposes.

Application of DSS confirmed that there were 10 gas and gas-condensate fields in 15 exploration areas of Yenusei-Khatanga depression and about 10 deposits in the drilled-out areas of Vilyui syneclise. The economic effect of the nuclear explosion made for these purposes was estimated at 160 million rubles in the prices of 1984.

3.2. External Excavating Nuclear Explosions

Excavating, loosening and spalling explosions are grouped with external explosions. A helpful effect of these explosions consists in breaking of rock masses and moving of the crushed rock to a new spot.

The program of peaceful application of nuclear explosions provided for creation of a wide network of man-made basins in the southern droughty districts of the country using nuclear explosions. This was explained by the necessity of supplying some State farms of Semipalatinsk, Kustanai, Tselinograd, Pavlodar and Guryev regions with water. Many State farms of the mentioned regions were located in the valleys of the rivers which were characterized by unsteady water run-off.

Making of underground excavating nuclear explosions is much more complicated compared with camouflet explosions due to the difficulties of radiation safety ensuring. Specific projects of applying excavating nuclear explosions justified their feasibility and economic advisability for creating water basins. According to various estimations and project studies in the late 60s, droughty regions of Kazakhhstan alone required up to 40 basins with the total area of 120-140 million m^3. They were also advisable for making dams to be used for power engineering and irrigation needs, canals for transferring some run-off of large northern rivers to the south to restore the level and exclude salinization of such vital inside basins as the Caspian, Aral Seas and the Sea of Azov.

Study of natural conditions showed that reservoirs in the form of deep craters capable of taking 3-5 million m^3 of water and having a small evaporation surface could be created in the river valleys to accumulate high water run-offs. The water retained with craters might be used for economic seasonal purposes.

Taking into account the features of nuclear explosions, the ground outburst explosion on the river Chagan, Semipalatinsk region was first of all planned.

A deep crater located in the river flood land is the main element of basins. A crater results from an excavating nuclear explosion. After that a canal connecting the river-bed with the crater is made in the explosion produced bulk. The canal is built by either exploding chemical HE and making a nuclear explosion at the same time or using conventional construction facilities after it.

The explosion in 1004 borehole was made in the river Chagan flood land on January 15, 1965. VNIIEF developed a special thermonuclear charge having 140 kt energy release was exploded at a depth of 178 m in sandstone slightly supplied with water and having bone coal and clay shale admixtures.

In twenty-four hours after the explosion the gamma-radiation dose rates in the crater and in the ground bulk were 20-30 R/h. Ten days later ~ 1 R/h radiation levels (D+10) were observed in the intended channel and dike area at a distance of 400-500 m from the ground zero. In about a month the route of the water-supply canal was broken down and the radiation levels at various distances from the explosion ground zero were measured. Radionuclides of induced activity made the primary contribution into the gamma-radiation dose in the epicentral explosion area.

Distribution of the dose rates according to the distance from the explosion ground zero and regularity of their changes in time prompted the simplest engineering approach. It consisted in starting activities aimed at making a supply canal on the spots having lower radiation levels and postponing activities on the spots with higher radiation levels. Moreover, it was found out that the content of radionuclides would reduce decreasing the radiation dose rate as the upper ground layers were removed with bulldozers.

The explosion produced a crater. The crater diameter on the initial surface was - 430 m, the bulk crest height was 20-35 m, the bulk width from the crater crest was - 400 m. The volume of the visible crater from the bulk crest was 10.3 million m^3, that from the initial surface was 6.4 million m^3. In the ground bulk area 30-40% of explosion produced radionuclides fell out. The bulk rocks blocked the river forming an explosion-stone rubble dam. In the spring of the same year the river-bed was connected with the crater by a canal to let the water from melted snow through the bulk rocks. Subsequently a stone and earth dike with water-carrying structures was built in the left-bank part of the bulk. Construction of the canal, supporting dike and spillways combined with the rock bulk created conditions for producing a basin that had about 17 million m^3 capacity including 6.4 million m^3 capacity in the crater. The external basin was used for fish-breeding and watering the cattle.

At this facility the sanitary protection zone was arranged. The radiation situation was periodically checked by the test site radiation safety service.

The explosion on the river Chagan was not optimal in all parameters of excavating nuclear explosions. The outburst value, that is the ratio between the crater radius and the nuclear device loading depth, was greater than one. As a result, an increased amount of the explosion products went into the atmosphere. Small radioactive fallouts were discovered beyond the test site.

In 1989-1991 the area of radioactive contamination around Lake Chagan was examined using aviation and ground gamma-ray spectroscopy methods.

A scale of 1:200,000 was used for survey at the altitude of 100 m. The velocity was equal to 180 km/h. The survey flight lines were oriented in wide directions. Under such survey conditions the crater was characterized by the dose rate of about 1 mR/h (the averaging interval was 800 m). The explosion was traced in a north-western direction and recorded within 5-6 km from the ground zero. Its dose rate level there was 15-25 μR/h.

Telkem-II explosion (multiple) was arranged at Semipalatinsk test site in 1968. This was a model explosion and it was set off to generate parameters of the multiple explosion initiated by three nuclear devices. It was made on the route of Pechora-Kolva canal to be located to the north of Perm region. This explosion was made in thin-bedded aleurolites and argillites interlayered with gray sandstones having a gas content of up to 3%. Three nuclear devices 0.24 kt yield each were placed in boreholes at a depth of 31.4 m. The distance between the boreholes was 40 m. The explosion produced a trench and a bulk of the ejected rock. The trench at the ground surface level was 142 m long, 60-70 m wide and 16 m deep. The bulk height ranged within 7 - 16 m.

Model explosions supported mechanical and seismic estimations and their results were used to design a multiple excavating explosion.

Experimental-industrial activities aimed at creating a trench under swamped locality conditions were performed in Perm region on the route of the future Pechora-

Kolva canal. Many scientists shared the necessity of building such a canal, which was explained by a great sinking of the Caspian Sea level (by 2.5m from 1935 till 1970).

Three nuclear devices having 15 kt energy release each were arranged in three boreholes at a depth of 127 m. The distance between the boreholes was 163-167 m. A simultaneous explosion of these devices at Taiga facility took place on March, 23 1971. It was made in the lower section of drowned aleurolites, argillites, marls and dolomites occurring at 70-135 m depth and in the upper section consisting of gravelly soils, sands and plastic clays which were also heavily drowned.

The explosion produced a trench 700 m long, 340 m wide and 10 - 15 m deep. It had stable edges and 8-10° angle of slope. The bulk of rocks bordering this trench was formed mainly due to the earth surface elevation and deformation and to a lesser extent due to the ejected soil.

In fifteen years after the explosion the gamma radiation dose rate on the bulk crest ranged within 60 - 600 μR/h. It made up 50 μR/h over the basin surface. The sanitary protection zone regulations were observed at this facility. Beyond the sanitary protection zone the radiation situation was maintained at the level of natural background. The facility was periodically inspected.

As calculations showed, excavating nuclear explosions were economically justified when the yield of a single nuclear device exceeded 10 kt. However, in this case it was impossible to ensure observance of the Moscow Treaty, 1963. Therefore, further activities according to this technology were brought to a stop.

Radioactive products of an external underground nuclear explosion that get in the atmosphere can be reduced considerably if the dome is kept from being opened during the explosion. This may be achieved in two ways.

The first way consists in a nuclear device loading on the mountain flank in a canyon. The explosion causes shattering of rocks and their rolling down the flank, which results in a rock-fill dam. Another approach is to make a heaving nuclear explosion on the even surface. The non-opened dome of rocks produces a bulk after falling that is higher than the initial surface due to the rock shattering factor.

“Lazurit” explosion in Murzhik locality of Semipalatinsk test site took place on December 7, 1974. It was made on the flank having 20° steepness. Quartzites and cherts formed the exploded rocks. The nuclear device having 1.7 kt energy release was exploded in the borehole at a depth of 75 m. The explosion produced a dome-shaped bulk of crushed rocks on the flank that was 14 m high and 200 m in diameter. The radiation levels during the explosion and after it were by 3-4 orders of magnitude lower than during excavating explosions.

“Kristall” explosion arranged at 3 km from Udachnaya settlement, Mirninsky region, Sakha Republic (Yakutia) was set off in permafrost limestone on October 2,

1974. Its aim was to create a dam-tailing storage facility for the concentrating mill of Yakutalmaz integrated plant. The nuclear device having 1.7 kt energy release was exploded in the borehole at a depth of 98 m. In 3.5 seconds after the explosion rocks elevated at a maximum height of 60 m, whereupon they settled down without dome opening. Isolated jet gas blow-byes were observed when the rock dome was falling. The explosion produced a bulk on the surface that had the form of a dome-shaped hill 180 m in diameter. Its average height was 10 m and it had a volume of 0.15-0.17 thousand m^3. The last gamma-beta survey of the heaved rocks and adjoining areas that was made in 1991 showed predominance of a natural radiation background (9-15 μR/h). Only in one confined area to the north-east the exposure rate was as high as 50-60 μR/h. After the bulk had been covered with rocks from the open cut (6 m thickness), the levels reduced to the background values. This facility was under periodical control.

The second way is to produce collapse craters. In this case explosions should be made at a certain reduced depth in failed sedimentary rocks. Semipalatinsk test site had no necessary geological conditions for such explosions. The most suitable geological conditions for producing collapse craters were available on Mangyshlak peninsula. Three explosions were arranged there in 1969-1970. The collapse crater produced by 2-Ò borehole explosion was 13.8 m deep and its radius was 150 m. After the explosion in 6-Ò borehole the produced crater was 12.8 m deep and its radius was 250 m.

In 1990 the sites of underground nuclear explosions made in 1-Ò, 2-Ò, 6-Ò boreholes on Mangyshlak peninsula were subjected to test inspections. They showed that the radiation levels at the crater bottoms were at the natural background level. Spring waters from the melted snow that got through the loosened rocks were filtered into the lower beds.

3.3. Intensification of Oil and Gas Extraction in Oil Fields

The search for the possibility of applying underground nuclear explosions in gas and oil extraction industry was included in the number of first-priority areas of investigations within the USSR program of peaceful application of underground nuclear explosions. In 1965 experimental-industrial activities using UNE under operational field conditions of Grachevsky oil deposit, Bashkiria (Butan facility) were for the first time performed by our country. Three low-yield explosions (from 2.3 to 8.0 kt) were set off in the body of the depleted oil deposit.

The results of these experimental efforts turned out to be positive:

- special nuclear items were made and successfully tested. The technique for their descent and lift in deep standard boreholes was completely developed;
- the criteria were specified and the possibility for a safe UNE under the operational field conditions was proved;
- production rates of the explosion boosted field boreholes increased by a factor of 1.5-2.0. The conditions were created that allowed formation of a gas cap in the deposit. It changed its mode of operation and made it possible to reduce the natural rate of the deposit pressure decrease and to increase the current oil output factor by 5-8%.

Successful operations at Butan facility promoted further expansion and development of these prospecting activities under various oil and gas field conditions.

In 1968 through 1987 experimental-industrial explosions were carried out at the following six facilities. In 1980 two explosions were made at Butan facility to improve conditions for implementing the technology of ore body development by gas-cap drive. Grifon (1969) facility at Osinskoe oil deposit that was a typical sheet oil pool with water drive. Helium facility (1981-1987) at Tyazhskoe oil deposit similar to Grachevskoe both in oil accumulation and in the type of the technology implemented here. Finally, two oil deposits being under exploration in the Western Siberia - Angara (1980) facility at Yesi-Yegovskoe and Benzol facility (1985) at Sredne-Balykskoe oil deposits.

At the most facilities nuclear explosions were carried out within the productive deposit strata. The exceptions were Grifon facility where explosions were made under the productive stratum (in the water-saturated horizon range) 70 m lower than the deposit water-oil contact, and Benzol facility where the explosion also took place under the productive stratum (in highly argillaceous bedrock).

In 1976 a large-scale industrial experiment was started using UNE. Its aim was to develop oil and gas resources at Sredne-Botuobinskoe deposit in Yakutia, Oka, Vyatka, Sheksna, Neva facilities.

According to the program of activities at Sredne-Botuobinskoe deposit, the recoverable reserves of oil (up to 30 million tons) and gas (up to 16 billion m^3) were to be transferred to industrial categories after eight camouflet nuclear explosions covering 400 km^2 area had been made. The estimated economic effect was expected to make up no less than 100 million rubles in the prices of 1988.

All the nuclear explosions caused no total radioactive contamination of the atmosphere or the field territory. There was only a negligible amount of radioactive gases that for a short period of time penetrated through two borehole mouths because of their leaking connections. The oil from the boreholes of all deposits except for

Osinskoe contained no traces of contamination with radionuclides during the entire period of operation.

Since explosions till late 1976 the radiation level in the test area of Osinskoe deposit (Grifon facility) was no higher than the background value. After deepening and completion of the so-called perforated borehole, which was done on the initiative of miners and against the project, radionuclides started migrating through the oil accumulation to the central explosion area and their small amounts were vented onto the surface. However, the radiation level at the experimental site was no more than the standard permissible values.

The results of studies and trial operation of oil deposits subjected to nuclear explosion effects made it possible to conclude:

1. Experimental and industrial operations proved the possibility for making safe UNE at the operational oil deposits without damaging field structures and dwelling houses and ensuring complete radiation safety of the attending personnel and population provided there were no violations of the design technologies and the field operation regulations.
2. The information about the character of UNE effects produced on carbonate collectors and hydrocarbons contained in them as well as on field structures and communications was obtained.
3. Underground nuclear explosions in the depleted field Grachevskoe resulted in decreased rate of natural oil extraction reduction almost by a factor of 3. In the field Osinskoe they increased the efficiency of the boreholes nearest to the source of effects (150-800 m) by 1.5 times. The current oil output factor at Grachevskoe oil deposit increased by 5-8% and at Sredne-Botuobinskoe oil deposit dry boreholes gave industrial oil and gas inflows after UNE.

In conclusion it should be noted that a large body of information about UNE effects upon rocks, carbonate collectors of oil wells was collected in the course of activities. Optimum technologically effective procedures for experimental-industrial operations at oil deposits using underground nuclear explosions were worked out.

3.4. Extinguishing and Elimination of Uncontrolled Gas Blowouts

Extinguishing of uncontrolled emergency gas blowouts using underground nuclear explosions is one of not many obvious peaceful nuclear explosion effects. Essentially, the method is as follows. Mechanical effects produced by explosion of the nuclear device arranged in the inclined borehole result in displacement of the rock mass, which is enough for complete borehole shutoff. The best way is to set off an explosion directly in the cover over gas accumulation. The following four emergency gas blowouts were extinguished in the Soviet Union using this method:

- gas field Urta-Bulak, Uzbek SSR, 30 September, 1966;
- gas field Pamuk, Uzbek SSR, 21 May, 1968;
- gas field Maiskoe, Turkmen SSR, 11 April, 1972;
- gas field Krestishchi, Ukrainian SSR, 9 July, 1972.

The fifth gas blowout in the gas field Kumzhinskoe of Arkhangelsk region, “Pirit” facility, was not extinguished using this method because there were no precise and clear geological and geophysical materials on the emergency borehole location. The gas jet in Urta-Bulak was the most vigorous of all 5 emergency blowouts.

In Urta Bulak gas field of Uzbek SSR a gas bed was uncovered during drilling at the unforeseen depth of 2450 m. It had an abnormal pressure of 300 atm. On December 1, 1963 the emergency gas outburst took place during drilling of borehole ¹ 11. It contained a large amount of hydrogen sulfide. The originated fire and the aggressive environment resulted in a fast destruction of the wellhead equipment.

For almost three years the blowout was being unsuccessfully eliminated using all the methods known in oil and gas industries, for which purpose three deep boreholes were constructed. The failure of operations was first of all explained by the following: a complicated situation on the emergency borehole mouth, an uncertain space position of its hole, a high blowout output.

Based on the estimations of specialists, the open flow potential of the borehole exceeded 12 million m^3 of gas per day with the formation pressure of 254 atm. Such amount of gas would have been sufficient for supplying a large city such as Leningrad.

On the instructions of the Council of Ministers passed on December 19, 1965, the USSR Ministry of Medium Machine Building and the Ministry of Geology studied the possibility of eliminating the gas blowout in borehole ¹ 11 located in Urta-Bulak field by setting off a camouflet nuclear explosion. A rational depth of the emergency borehole shutoff was chosen.

According to the order given by the Minister of Medium Machine Building Ye.P.Slavsky, VNIPI Institute of Industrial Technology worked out the scientific substantiation and then the project of these operations. Ye.A.Negin, the chief designer of VNIIEF, was appointed Chairman of the State commission.

Specialists of VNIIEF developed and delivered a new special nuclear device to Urta-Bulak deposit. From February till September of 1966 two inclined boreholes were being drilled and expanded to a diameter of 445 mm. A nuclear device with 30 kt energy release was dropped into one of the boreholes at a depth of 1532 m.

The distance between the container mounting position and the emergency borehole was 35 m, that is at the moment of explosion borehole ¹ 11 was in the area where the passing compression wave stress ranged up to 1600-25,400 kg/cm^2 and over and à horizontal displacement of rocks in the mass was 0.41-1.3 m and over.

Owing to this fact, one could expect a complete elimination of this blowout as a result of the column and emergency borehole displacement relative to the original position.

The explosion was set off at 9 am of Moscow time on September 30, 1966. It was made in the presence of the minister Ye.P.Slavsky.

Gas escape from the emergency borehole stopped completely in 22-23 seconds after the explosion and the jet died away.

No radioactive products emerged on the surface and got in the boreholes drilled at the deposit.

Thus, due to the prepared and performed explosion the open gas blowout deposit was completely eliminated at Urta-Bulak deposit without complicating its subsequent industrial development. The economic effect in this case made up 25 million rubles (the prices of 1966). The blowout elimination efforts took 270 days instead of the previous three unsuccessful years. Billions of cubic meters of natural gas were saved.

3.5.Creation of Underground Cavities

Intensive development of gas, oil, chemical and oil refining industries necessitated expansion of the tank farm in the country. The lack of tanks for the industry needs was especially critical in the 60s when development of large gas-condensate fields started. It was necessary to create tank farms directly in the fields close to gas pipelines, industrial and civil facilities.

The existing conventional tank construction methods prevented from satisfying increasing demands for high-pressure tanks. Construction of overland steel reservoirs requires a great amount of metal and high costs of construction and assembling operations. Large-sized areas are allotted for their disposing and expensive fire and explosion prevention measures are taken. A shaft method of creating underground tanks requires great capitalized expenses and takes much time for their construction. The method of washing chambers in rock salt deposits with water has limited capabilities because of a long duration of the process and transformation of large bulks of fresh water into biologically harmful brines to be disposed of.

On April 22, 1966 a phenomenological experiment A-I having 1.1 kt yield was carried out at Azgir site at a depth in salt of 161 m. This explosion was similar to the American explosion Gnome (December 10, 1961) whose yield was 3 kt. The second explosion À-II having 27 kt energy release equivalent was made on July 1, 1968 at a depth of 590 m and in the same salt dome. A durable cavity was produced that is still intake. Its volume is 150 thousand m^3. The cavity À-I was quickly filled with water through the cracks on the earth surface that reached the dome roof. The cavity À-II was filled with water getting through the borehole where through the nuclear device was dropped because of its unsuccessful hermetic sealing. Both experiments were important steps in development of methods used for creating underground cavities for storage of natural gas and gas condensate.

The first explosion aimed at making an experimental reservoir was set off in Sovkhoznoe field, Orenburg region on June 25, 1970. It produced no negative effects on the operational field and surrounding industrial and civil structures. The cavity 11 thousand m^3 in volume was made in a rock salt mass at a depth of 702 m. A few months later the reservoir was opened up through the end box and in 1971 it was sealed with natural gas at 60 atm pressure. The cavity was operated for 11 years. In 1993 operations for its isolation started.

In 1970 through 1984 three large underground tank farms with the total design volume of 866,000 m^3 were constructed in the three largest gas condensate fields of the country using nuclear explosions. These were Orenburg, Astrakhan, Karachaganak fields having the total output of gas over 60 billion m^3/y, gas condensate – 8.6 million t/y and sulfur – 5.3 million t/y.

Industrial nuclear explosions in rock salt reservoirs allowed the following progress to be made:

- for almost 20 years 2 reservoirs in Orenburg fields were being operated as gas condensate storage facilities. They prevented from irretrievable losses of more than 2 million tons of valuable petroleum products;
- for the first time in the world six storage facilities were created at once (200,000 m^3);
- Astrakhan gas and chemical complex was put into operation without gas condensate losses due to application of nine reservoirs for stockpiling a gas condensate mixture to unload production lines for producing sulfur, tank gas and fuel. Since some reservoirs were for a long time in an empty condition at a high formation temperature, the volumes of these cavities reduced to the value having no industrial importance;
- putting into service of five reservoirs at Karachaganak gas condensate complex was completed. They were designed for gas separation and annual production of about 1 billion m^3 of quality standardized gas and 500 thousand of gas condensate in each reservoir;
- the possibility of leakage-free storing of gas at a pressure of 140 atm was proved;

- a simple safe pattern of operating reservoirs through the restored end box was demonstrated. It consisted in gas condensate forcing out by natural gas;
- the prediction was supported according to which contamination of the stored gas condensate with radionuclides was excluded.

At the same time the experience of making and operating reservoirs testifies to the necessity of providing a high quality of operations and production culture at all the stages. It also shows that design approaches should be implemented with scrupulous adherence, otherwise untimely losses of net reservoir volumes are inevitable.

One more way of real application of the underground nuclear explosion energy is disposal of biologically harmful industrial effluents in deep-seated geological formations. An underground nuclear explosion increases the filtration area, which makes it possible to increase drastically the efficiency of the boreholes used for injecting effluents into deep interior. The produced explosion cavity and the caving column together with the fracturing zone are the filtration area through which industrial effluents are injected.

At Sterlitamak sodium carbonate and cement plant of the production association “Soda” the sewage volume was about 60,000 m^3/day. To eliminate waste waters, an enlarged injection borehole was made at Kama facility, for which purpose a nuclear explosion was set off on October 20, 1973. Since 1976 the site for underground disposal of biologically harmful industrial effluents was put into operation. During 14 years of this site operation more than 20 million m^3 of industrial effluents containing over 1000 t (0.05 g/l) of suspended solids were injected into deep-seated isolated beds.

Industrial effluents disposed of at this facility are highly toxic and resistant to the known purification methods. Moreover, they are characterized by extremely high content of suspended sediments sometimes ranging up to several hundreds and even thousands of mg/l, these sediments being presented by resinous substances. Disposal of such industrial effluents through conventional boreholes is almost impossible.

The engineering process of underground disposal of industrial effluents through enlarged boreholes is monitored by geophysical measurements in observation boreholes drilled both to the mining floor and to the overlying water beds.

At Kama-1 and Kama-2 facilities the state of water-bearing strata lying above the intercalated confining bed was monitored using piezometric boreholes and the state of water-bearing strata lying above the main confining bed was checked through hydrogeological boreholes. The observation results showed that the injected industrial effluents had not penetrated into these formations.

When filtering the injected industrial effluents through the explosion area contacting with radioactive melt, some radioactive products got into the injected liquid. However, in 5-6 months after injection the specific activity of industrial effluents even 500-1000 m away from the injection borehole reduced almost to the background values due to heavy dilution with new injected portions, mixing with brine water and adsorption of radionuclides on the rock skeleton surface. This testifies to the safety of the method used for depth disposal of industrial effluents.

According to the customers′s data, the activities at the mentioned sites prevented from causing damage to the environment and saved more than 60 million rubles (in prices of 1982).

The new developed method of underground disposal has rather wide opportunities for implementation. The studies have shown that the geological feature of large territories in the Russian Federation is favorable for construction of similar facilities at 1000-2000 m occurrence depth of lost circulation horizons. This is first of all a large territory of the European part (the Volga river region, Ryazan, Orenburg regions) and many regions of Siberia.

3.6. Prevention of Coal Dust and Methane Blowing in Coal Mines

Coal and gas blowing in Donbass mines can be explained by mining at a depth lower than 700 m from the earth surface, by increase in the ground pressure and growth of stress in the environment. Thus, during fifteen years 235 gas and coal dust blowing events were recorded at “Yunkom” (“Young Communards”) mine in Yenakievo town. 60 miners perished.

The most effective blowing-prevention method such as an advance development of protection beds is limited by the fact that protection beds become blow-dangerous as mines get deeper. Therefore, search for efficient methods preventing this terrible phenomenon is a topical task.

The scientists from the Institute of Technical Thermal Physics, the Ukrainian Academy of Sciences and VNII of Industrial Technology proposed the method of preventing coal and gas blowing in mines using nuclear explosions. The idea of this method is as follows. The explosion-generated wave having high parameters of stresses and vibratory displacements produces intensive effects in coal-bearing section rocks and coal beds within the space of hundreds of meters. They result in the change of the stressed-strained state, cracks are produced, which causes the field flattening and degassing of beds. In the long run, the probability of blowing reduces.

In this connection the experiment was carried out in “Yunkom” mine, Yenakievo town of Donetsk region, Klivazh facility whose aim was to check efficiency of blowing-prevention measures by processing the most blow-dangerous beds with a nuclear explosion.

The explosion having 0.3 kt yield was made at a depth of 903 m on September 15, 1979. The eastern side of the mine field was involved. The nuclear device was placed between the coal beds Devyatka and Kirpichevka at 45 and 31 m distances, respectively.

The end box was constructed in the slope 826 m away from the horizon. The explosion yield was conditioned by ensuring seismic safety of mine shafts and main workings as well as of industrial and dwelling surface buildings near to "Yunkom" mine and in Yenakievo town.

The underground workings in the mine were examined twenty-four hours after the explosion. No serious damage was found except for the cave on the lava and vent gallery joining. Some rock fragments fell out and fines crumbled off the cover and sides of the workings.

This explosion produced no negative effects on the mine and the neighboring enterprises and did not interfere with the active life of the inhabitants. Seismic and radiation safety was provided as it was specified in the project. On the fifth day after the explosion the mine was working in a normal mode.

In 1980-1982 the character of blowing in Yunkom mine changed greatly in spite of carrying over to 826 m horizon: the density of gas dynamic events was less than 1 per 1 million m^2 and the intensity of one event was less than 50 t, which was 4-5 times less than on overlying horizons.

This experiment did not affect technical and economical characteristics of Yunkom-6 mine and when developing blow-dangerous beds directly in the explosion area about 800 thousand tons of coal were mined.

According to the resolution of the Ministry of Coal Industry that appreciated the experimental results, the second explosion was to be made in Rumyantsev mine located close to Gorlovka town in Donetsk region, but the work was suspended because of the moratorium and collapse of the Soviet Union.

3.7. Breaking of Apatite Ore in Rock Mass

Underground large-scale ore deposits can be developed using block induced caving systems. To break a mass with ore reserves of 1 million tons, 2-4 km of workings should be covered and deep boreholes about 10 thousand meters long should be drilled. Up to 500-600 t of chemical HE are arranged in them. The costs of workings, boreholes, explosives and breaking labor efforts are as high as 30-40% of the ore extraction cost.

The possibility for applying the enormous energy concentrated in a small nuclear device volume allowed preparatory operations necessary for breaking huge ore volumes in one explosion to be simplified and minimized.

Specialists from VNII of Industrial Technology offered the method of breaking ore bodies with nuclear explosions. According to this method, a cutting gap and a horizontal undercut acting as a clear and compensation area that reduces the broken ore compaction level are made at a distance of 45-60 m/kt$^{1/3}$ from the end box.

A cutting gap and an undercut increase the volume of the broken and extractable ore by a factor of about 10 as compared with the camouflet explosion using no gap and undercut.

Trial operations aimed at experimental estimation of technical feasibility and economic advisability of nuclear explosions for ore breaking were performed in 1969 through 1990 at Kuelpor deposit, Dnepr facility that is 21 km away from Kirovsk town of Murmansk region.

The operations were performed in a separate area consisting of some ore body 30-60 m thick and about 200 m long, two tunnels and temporary buildings on the surface. Two nuclear explosions were made to break the ore: a single explosion of 2.1 kt yield made on September 4, 1972 and a group explosion (two nuclear devices having 1.7 kt yield each which were 75 m away from each other) that was arranged on August 27, 1984. The single explosion broke the block of $50\times50\times50$ m^3 , the group explosion broke $50\times125\times90$ m^3 block. The amount of the broken ore in these two blocks made up 1550 thousand tons.

The experiment features consisted in the fact that the broken blocks were outlined with the vertical cutting gap on the opposite side of the nuclear device and the horizontal undercut was provided at the base of the blocks.

Consumption of chemical substances for the secondary breaking of bulky fragments was several times less than during ore breaking with borehole charges of chemical substances in mines and made up 12-13 g/t instead of 800-1000 g/t, respectively.

During these studies 400,000 tons of ore broken with nuclear explosions were extracted from the test blocks. It was found that the quality of breaking was higher compared with the conventional technology applied in the mines of Production Association “Apatit”. The analysis made of the borehole ore showed that the concentration of radioactive products in the mined ore was no more than the permissible concentrations and was less than 2 Bq/kg for Sr-90 and less than 5 Bq/kg for Cs-137.

One of the interesting technological features of the described experiment at Dnepr facility was creation of the system controlling radiation explosion effects.

Essentially, the problem was as follows. The explosion products were ejected through the special channel into a free large insulated space where they were confined. Such explosion conditions may be considered prototypes of the U.S. Marvel nuclear test carried out at the Nevada test site on 21 September 1967, and the Soviet nuclear explosions conducted in tunnel 148/1 on 9 April 1971 and in tunnel 148/5 on 16 December 1974 at the Semipalatinsk test site. The explosion products were taken out aside from the broken block thus reducing the contamination level of the space close to the cavity and probability of the broken ore body contamination. Specialists examined the disposal chambers in more detail and the sampled material was studied.

Mining conditions and radiation situations at the work places were almost no different from the normal ones during ore extraction and there was no need of mining and radiation limitations.

All the operations at the described facility were completed and the set tasks were fulfilled. Currently the experimental mine is no more operative. The local organizations of the Sanitary and Epidemiological Control Committee and Minatom specialists monitor the mine area according to the plan.

Thus, the experiments carried out under full-scale conditions for the first time in the world practice permitted generation of the data that can be used for solution of all the problems related to application of nuclear explosions for breaking ore bodies and their subsequent extraction.

3.8. Nuclear Explosive Generation of Isotopes

In the early 60s VNIIEF showed its interest to application of nuclear explosion neutrons for production of various isotopes. Neutrons affect the targets arranged in the nuclear device or close to it. Three types of neutron effects on the target are possible:

- neutron detachment from the target nuclei due to (n,2n) reaction;
- single capture of neutrons by the target nuclei;
- multiple capture of neutrons by one nucleus.

Th-232 and U-238 nuclei were considered as the targets. In the first process Th-231 and U-237 nuclei are produced that turn into Pa-231 and Nð-237 through beta decay. Neutron reactor exposure converts them into U-232 and Pu-238. These isotopes may be used as isotope sources of energy. In the second process Ðà-233 and Np-239 are produced that turn into U-233 and Pu-239 fissile matters. In the third process a whole spectrum of transuranium elements is produced on the target of U-238. These isotopes may be also produced in reactors or accelerators.

To produce these isotopes by a nuclear explosion and consider production of not only indicator but industrial amounts also, the method of extracting the explosion built up matters should be provided. One of the approaches suggested by Yu.N.Babaev and Yu.A.Trutnev (Arzamas-16, VNIIEF) consisted in confining of explosion products in a steel chamber, making a set of explosions in it and extraction of the built up product. Another approach was underground explosions made in such environments that would later allow chemical extraction. In an underground explosion useful products mix with the rock expanded by the explosion. In case of a silicate, that is water-insoluble rock a large-scale extraction of the products mixed with it is almost impossible. This fact drew attention of A.S.Krivokhatsky from the Radium Institute and Yu.S.Zamyatnin from VNIIEF. Rock salt was the most suitable environment for the activities of this kind, which was supported by the publications dedicated to the studies into the American Gnome explosion products. According to the data of the Radium Institute, this approach provides ~100-fold natural enrichment. Salt contains 1-2% of water-insoluble admixtures-carriers of explosion products. Solution of salt results in a sediment isolation and thus in a target product enrichment. Separation of explosion products from the water-insoluble sediment also seems to be not a difficult matter.

After termination of air tests and switchover to underground tests the question of a calibration test in rock salt arose.

The Radium Institute (A.S.Krivokhatsky, D.S.Nikolaev) proposed a salt dome Bolshoi Azgir situated in the western outskirts of the Prikaspijskaya salt-bearing provinces as an experimental site “À”. Test explosions at this site were made by VNIIEF together with VNII of Industrial Technology responsible for mining operations and the Radium Institute that was in charge of chemical and radiochemical experimental parts. This experimental site came to be known as Galit.

The first explosion À-I of the standard nuclear device having a small energy release of 1.1 kt was made at a depth of 160 m on April 22, 1966. The cavity was produced, but the fractures around the cavity joined the water-bearing stratum located in oversaline deposits. The cavity was quickly filled with water because of a small nuclear device loading depth and the explosion site location near to the salt dome end. Later this cavity was used by VNII of Industrial Technology and the Radium Institute to try the methods for extracting bottom sediments containing the explosion products. A hydraulic hoisting machine-air lift was mounted that took out the bottom sediments onto the surface. After that it was sequentially passed through the apparatus where salt was dissolved, insoluble particles were settled out, actinides were separated from them and other enriching operations were performed. About 2 tons of the bottom salt were extracted and processed. A small portion of sediments was passed through the entire separation chain and a symbolic amount of plutonium (70 mg) was produced.

Needless to say this was not a built up plutonium, but the non-combusted part of the matter loaded into the nuclear device.

The following experiment À-II was conducted at a depth of 590 m on July 1, 1968. Its yield (27 kt) was much greater than that of the first one. The produced cavity volume was about 150 thousand m^3. No special measures were taken to isolate the cavity from water-bearing strata and as in the previous case it was filled with water in a week.

The cavity À-II filled with water was used for making six 0.01-0.5 kt explosion experiments in 1975 through 1979. By that time the concept had been formulated according to which multiple explosions in one cavity should be made to obtain great amounts of explosion produced matters. As a result of such an approach, the explosion produced actinides would build up at the cavity bottom and extraction operations could be performed after explosions and accumulation of a certain amount of useful products. To prevent melt accumulation, it was proposed to make explosions in a cavity partially filled with water. Water was the working body that absorbed the explosion released heat.

The aim of low-yield water experiments was to study distribution of actinides in the water environment and to develop completely the methods for their chemical isolation and extraction. Among other things, a set of explosions allowed development of the technique for a fast entry into the cavity after the next explosion and reduction of the interval between the explosions. The minimum achieved interval made up 16 days.

The first “dry” cavity having a small volume was produced beyond the site Galit in Sovkhozny field (the north-eastern outskirts of the Prikaspijskaya salt-bearing provinces). Stability of rock salt cavities and the possibility for producing dry cavities made it possible to reorient towards multiple explosions using the cavity as a chamber for making such explosions. It was proposed that extraction operations should be performed after a set of explosions had been completed and a rather large amount of useful products had been accumulated.

As is often the case in the basic and especially applied science, a shift of the aims took place in the course of research and practical activities. First, rock salt was considered as the environment suitable for making explosions. It was convenient because various explosion produced actinides were easily extracted owing to its solubility. Then the elastic-plastic salt properties owing to which the explosion produced cavity would retain its stability happened to be no less interesting.

The third explosion made at Azgir site on December 22, 1971 was aimed at making a dry cavity having greater dimensions and checking the possibility for explosion production of Ðà-231 and U-233. Special measures were taken to prevent water getting into the cavity such as a telescopic casing of a borehole with steel tubing that shut off communication with water-bearing strata. The inside tube went deep into the salt for 70 m. The cement plug 100 m long was in the tube with its upper section and its lower section was in the uncased borehole. The explosion depth was taken equal to 1000 m to ensure greater reliability. Later such a depth was approved operational for many explosions. The produced dry cavity had a volume of about 200,000 m^3. The bottom sediment samples confirmed production of 0.5 kg of Đà-231 and 2.5 kg of U-233.

It can be said that the artificial protactinium field that is the only on the Earth was created in this way (protactinium being in radioactive equilibrium with uranium-235 can be found in uranium ore in $0.35 \cdot 10^{-6}$ proportion to the natural uranium).

In March of 1976 a repeated explosion À-III-2 was made in the dry cavity of A-III explosion.

On July 29, 1976 À-IV explosion was conducted at the same depth of 1000 m as the third explosion in 1971. Its aim was to check the explosion produced plutonium build-up. Studies of the cavity and the bottom sediments carried out after the cavity had been opened showed that actinides were located in the thin layer at the bottom of the melt lens. The cavity filled with salt vapors and evaporated structural materials of the nuclear device was getting cold as follows. First, condensation of more refractory metals incorporated into the nuclear device took place. These new-formed particles covered the cavity bottom filled with liquid salt. The salt got solidified and formed the lens having a segment shape and including a thin actinide concentrate layer. The explosion produced 15 kg of Pu-239.

On September 30, 1977 “there was another explosion À-V” conducted at a depth of 1500 m. This explosion was aimed at estimating the cavity convergence at this depth, that is the volume reduction under lithostatic pressure effects. The energy release was not high and thus the cavity volume was not great either. It was specially filled with water and based on the water flowing out of the borehole the volume reduction rate was determined. It was a bout 0.2 m^3/day.

The generated results were used to consider the problem of applying cavities of Galit site for disposal of radioactive wastes, of Russian NPP and Kazakhhstan wastes in particular.

3.9. Application of Nuclear Explosive Technologies for Solution of Global Ecological Problems of Modern Civilization

3.9.1. Some Features of the Nuclear Explosive Technology for Elimination of Chemically Toxic Materials

The nuclear explosive technology (NET) for elimination of chemically toxic materials (CTM) proposes thermomechanical destruction (evaporation, melting) of containers with eliminated substances, decomposition of ÕÒÌ loaded with a shock wave (SW) of a nuclear explosion (NE), conversion into nontoxic agents and their disposal at the explosion site.

Development of nuclear explosive technologies for elimination of chemically toxic materials was started in RFNC-VNIIEF in the late 80s. Its objective was to create a cheap alternative method for elimination of especially dangerous toxic materials produced both for military and civil purposes. The topicality of these activities was caused by extermination of chemical weapons (CW) and toxic agents (TA). This problem became pressing because the CW and TA extermination convention was concluded and such aspects as a low productive capacity, great costs and complicated ecological guarantees of the plants reprocessing chemical weapons and toxic agents were of great concern.

When this issue was discussed with the U.S. specialists in 1992, it turned out that the same principles for NET were formulated in the United States in the early 80s on the U.S. DOD initiative.

High characteristics of NET for elimination of CTM and its multipurpose character for a wide range of chemical substances make this technology very promising for removing the most toxic chemical substances from the environment. Besides, of great importance is an extremely peaceful character of this technology that has nothing to do with nuclear tests.

During a nuclear explosion:

- the eliminated materials are subjected to shock-wave loading with the nuclear explosion produced SW propagating through the package of containers with chemically toxic materials. CTM compress, get heated and then decompose to produce atomic states or more elementary molecules;
- at the next stage decomposition products expand, their density decreases, they mix first with structural materials and then with the ground melt. The environment gradually gets cold. In this case decomposition products recombine into new compounds in solid and gas phases that should meet the ecological safety requirements;

- in getting cold solid decomposition products of CTM become vitreous in the melt and gaseous products are kept from fast escaping by rock and the system of protection structures of an underground nuclear explosion;
- make-ups of decomposition products may be greatly affected by structural materials that are destroyed, decomposed and disposed together with CTM, by rock composition and the presence of special chemical substances used for shifting equilibrium of recombination products.

NET for CTM elimination must provide meeting of the ecological safety requirements traditional for underground nuclear explosions. They are as follows:

- seismic safety;
- radiation safety during NE and immediately after it;
- long-term radiation safety of disposed products as well as chemical safety of CTM decomposition products both during the explosion and in NET implemented disposal.

Seismic safety of NET is governed by the criteria worked out for underground nuclear tests.

Explosion radiation safety of NET is governed by:

- the criteria worked out for underground NE;
- technological conditions limiting the level of CTM gaseous decomposition products affecting the system of protection structures.

Long-term radiation safety of NET is governed by:

- the criteria worked out for underground nuclear tests (dilution of radioactive explosion products and their holding in a chemically inactive melt of rocks: low levels of fluid flows at the disposal site);
- the possibility for additional decrease in the disposed activity of explosion products due to special technological explosive devices producing reduced radioactivity.

Explosion chemical safety of NET is governed by:

- nontoxic composition of a gas phase of recombination products of eliminated CTM (due to selection of the loading level, selection of CTM to be eliminated, application of special chemical additives);
- sorption rock properties;
- total reduction in a gas phase of decomposition products.

Long-term chemical safety is governed by:

- nontoxic or low-toxic composition of a solid phase of CTM decomposition products (due to selection of CTM to be eliminated, selection of the loading levels, application of special chemical additives);

- chemical inactivity of the rock melt fixing a solid phase and a low level of fluid flows;
- sorption rock properties.

To guarantee NET efficiency regarding CTM elimination and safety of decomposition products, each type of CTM to be eliminated by NET is supposed to be experimentally studied at laboratory facilities simulating types and levels of technological explosion effects. According to these studies, the elimination efficiency as a function of the loading level should be determined for each type of eliminated CTM and the criteria for their NET elimination should be worked out.

To this end, special laboratory facilities were developed that were used to study behavior of various chemical substances under extreme conditions.

This engineering process component makes it possible to predict NET results during elimination of specific CTM.

Though NET is fundamentally capable of eliminating a variety of CTM and merely chemical substances (first of all, organic compounds), selection of CTM for their elimination with NET should be also determined by cost effectiveness. With gigantic production of chemical wastes in the world this condition means that:

- NET reprocesses individual groups of especially toxic materials whose elimination with plant methods requires great economic costs and entails a very high risk;
- materials to be eliminated by NET are delivered in a concentrated form, that is why their amount is not too great for NET capabilities (NET specific efficiency is determined by the total amount of eliminated materials that includes CTM, structural materials, technological additives, etc);
- materials to be eliminated should be generally NET reprocessed together with their containers.

Such CTM as toxic agents that are the basis of chemical weapons meet the considered requirements. Specific features of NET application for these purposes will be discussed below. As for civil-purpose CTM, everything is determined by the specific economic effect compared with plant technologies and NET extent (with a relatively low cost of NET and its high efficiency the number of technological explosions that may be made every year will be always limited).

Application of NET for elimination of chemically toxic materials should be available for various members of the world community. Nuclear states or a special international agency ensuring guarantees in the field of NW nonproliferation and only providing a civil character of NET activities should make the considered efforts for non-nuclear states based on mutual agreement.

NET application activities, ensuring of ecological safety at the technological explosion preparation stage, explosion making and monitoring of the environment condition after the explosion should be under international control.

Development of elements comprising nuclear explosive technologies may propose collaboration of specialists from both nuclear and non-nuclear states.

3.9.2. Nuclear Explosive Technology for Disposal of High-Level Waste of Atomic Power Engineering

The problem of handling long-lived high-level waste (HLW) of atomic power engineering produced in fuel cycles of NPP nuclear reactors is one of the fundamental ecological problems of civilization. As compared with other technologies, NET allows the specific activity of materials to be drastically decreased (several orders of magnitude) due to their dilution in the rock melt. It provides a material high chemical inactivity due to its transition into the magmatogene vitreous melt that is disposed at high depths and far from active life areas. It also ensures ecological safety of such a disposal.

NET for HLW disposal had been developed by RFNC-VNIIEF starting in the late 80s, but it was not experimentally implemented. At the same time many elements of NET for disposal of HLW were almost completely developed in the course of underground nuclear tests where the underground nuclear explosion (UNE) itself provided build-up of the activity, its dilution in the rock melt, vitrification in it during its getting cold (with appropriate rock selection) and disposal.

It should be mentioned that the nuclear explosive technology for disposal of HLW differs from UNE activity disposal first of all in the activity composition and the character of its change in time.

Now the nuclear power engineering of the world has achieved such a level when the problem of ecological safety of handling NPP radioactive waste has acquired a global character. A standard nuclear reactor having $Ð_{el}$ = 1 GW electric power produces yearly (given the average rated load factor is ~ 75%) the amount of nuclear energy that is equal to that released by Å = 15 Mt nuclear explosion. However, the same nuclear reactor also produces the amount of high-level fission products (FP) which is similar to that of Å = 15 Mt nuclear explosion. Since the total world nuclear power engineering level is as high as P_{el}^{Σ} = 350 GW, this means that the annual production of FP in NPP is equivalent to their build-up in nuclear explosions with a total yield of $Ì^{\Sigma}$ = 5250 Mt, which exceeds greatly the power of the entire nuclear arsenal. The power of the U.S. nuclear power engineering is estimated at $Ð_{el}$ = 96 GW and the power of the RF nuclear power engineering is $Ð_{el}$ = 20 GW, which constitutes ~ 27.5% and 5.7% of high-level FP produced in the world.

After the spent nuclear fuel (SNF) has been discharged from the reactor, it is kept at NPP for some time (normally for $\Delta t = 5$ years). Thereafter it can get to the temporary SNF storage facility generally also located on the territory of NPP or it is subjected to radiochemical treatment. After that SNF or some of its reprocessing products go for long-term storage that will be ecologically safe in terms of historical time scales. Currently, various approaches to this problem solution are being considered, but it has not been solved yet. It should be noted that storage of enormous amounts of radioactive waste at NPP is not a good idea because NPP are normally located in active life areas and accidents at temporary storage facilities may result in large ecological disasters.

If SNF or its reprocessing products are aged for 15 years after discharging, the absolute activity of FP is mainly determined by the activity of two radionuclides such $Sr^{90}+Y^{90}$ and $Cs^{137}+Ba^{137}$ having specific half-life values of $T_{1/2} \approx 30$ years. The absolute value of this activity component is $\tilde{N} = 7\cdot10^6$ Ci for specific power output of $Q_{el} = 1$ GW per year.

If the SNF aging time is $\Delta t \geq 200$ years, the absolute value of its activity will be estimated by the actinide component (reactor-grade plutonium Pu, Am and Cm^{244}) produced from original isotopes (mainly U^{238}) of the uranium-uranium (U^{235}_{α}, $U^{238}_{1-\alpha}$) nuclear fuel. The absolute value of this activity component (at $\Delta t = 200$ years) is $C = 1.1\cdot10^5$ Ci for specific power output of $Q_{el} = 1$ GW per year (we note that this value may vary greatly according to the types of nuclear reactors).

In some states SNF is produced or is supposed to be reprocessed to isolate reactor-grade Đu and return it into the fuel cycle of NPP for subsequent burning out in thermal-neutron reactors (as a part of a special uranium-plutonium nuclear fuel) or in fast neutron reactors. Because of a high activity and radiotoxicity of reactor-grade Đu and its potentialities for application in nuclear and radiological weapons, such a program of its handling may cause strong objections.

The matter with Am that may make up an essential portion of the long-term actinide activity also remains unsettled.

During radiochemical reprocessing of SNF long-lived fission products with the half-life of $T_{1/2} \geq 10^5$ years may be isolated including such radionuclides as Se^{79}, Tc^{99}, Zr^{93}, Pd^{107}, Sn^{126}, I^{129} as well as Sm^{151} with $T_{1/2} = 90$ years. They may pose a serious ecological problem despite a rather low (compared with other SNF components) activity level: $C_{\Sigma} = 10^4$ Ci with Sm^{151}, $C_{\Sigma} = 500$ Ci without Sm^{151} for specific power output of $Q_{el} = 1$ GW per year.

Thus, the following types of high-level waste are considered the basic ones for NET:

- fuel assemblies (FA) with SNF for the reactors whose SNF undergoes no radiochemical reprocessing;
- faulty FA of any reactors;
- individual components of SNF radiochemical reprocessing that undergo no further recovery including high-level FP, actinides, long-lived FP.

The possibility for creating a multipurpose technology reprocessing such diversified types of HLW is undoubtedly of great scientific, technical and practical interest.

The concept of NET for disposal of HLW is based on the following basic principles:

- application of a nuclear explosion energy for producing a magmatogene silicate melt and dilution of the disposed activity in it;
- transition of the cooling melt into a vitreous chemically inactive state similar in its properties to the materials realized in plant technologies for HLW vitrification, but having a much lower (orders of magnitude) activity concentration level;
- disposal of HLW reprocessed by this method at large depths and far from active life areas;
- practical impossibility of using NET reprocessed materials for weapons purposes;
- ecological safety of technological operations.

NET can reprocess HLW (including SNF) received directly from NPP and thus exclude an expensive and potentially dangerous cycle of radiochemical reprocessing or treat non-recoverable products of radiochemical HLW fission. A particular choice is governed by evolution peculiarities of NET consumer′s nuclear power cycle.

To arrange an explosive technological device and disposed materials in the selected rock mass, a horizontal (a tunnel) or a vertical (shaft) deepening is made having a section that allows the required materials to be transported.

The end of the deepening is provided with the gallery for the chamber where reprocessing takes place.

The specific tunnel section ensuring transportation of the majority of reprocessed materials is $S = (10\text{-}20)\ \text{m}^2$. A sufficient variety of NET operations may be performed in shafts having the section that meets $\varnothing \approx 3$ m condition. When performing some types of technological operations (such as disposal of nuclear power plant members), large flow sections may be required. The depth at which the gallery for the reprocessing chamber is laid down is governed by the technological explosion safety requirements and depends on particular geological conditions and ground composition.

The materials to be reprocessed are arranged around the technological explosive device and together with structural members form a package whose loading level during an explosion is sufficient for their evaporation. The specific total mass of such materials is 70 t/kt of NE yield and it corresponds to the ground mass normally evaporated during an underground NE. It should be emphasized that the value of this mass is determined by all structural members necessary for arranging reprocessed materials (including such as the mass of destroyed protection containers).

Under these conditions the NET chamber with the treated materials may be considered as a small disturbance for the ground melting process, mixing of substances, ensuring of the ecological explosion safety. The mass of the treated materials is actually 10% of the NE produced melt mass (700 t/kt).

When using NET, a short-term radiation explosion safety (no radioactivity penetration onto the surface including abnormal escape of radioactive noble gases - RNG) is provided, as in an underground NE, by selection of the required geological explosion site structure, the depth of the explosive device loading and the system of protection measures in the tunnel (shaft) hole. The level of the rock gas content (for example, no more than a few percent, which is realized in granite rock) may be important in this case.

In this respect the fact that the disposed activity contains no great amounts of RNG comparable to the level of their build-up in NE is essential.

In ensuring a long-term radiation safety NET also rests upon the practical experience of the developed technology for carrying out underground nuclear tests where a great amount of activity is produced and disposed at the same time. If the disposal aging time after a nuclear explosion is $\Delta t = 1$ year, the activity concentration of fission products in the disposal melt will be estimated at ~ 10^{-5} Ci/g with reduction to ~ $6 \cdot 10^{-7}$ Ci/g in $\Delta t = 10$ years after the explosion. This corresponds to low-level wastes according to the classification. In the time period of $\Delta t = 100$ years after the explosion the activity level of fission products will reduce by about ~ 10 times and will make up ~ $6 \cdot 10^{-8}$ Ci/g. Later on the activity of fission products will go on decreasing and the actinide activity estimated at $2 \cdot 10^{-7} \cdot \AA^{-1}$ Ci/g, where $\AA$ is the explosion yield in kt (this value may vary noticeably and we give its typical level), will make a great contribution into the absolute activity disposal level. If $t \geq 100$ years, the NE activity disposal level will be close to the activity of uranium ores estimated at ~ $4 \cdot 10^{-8} \cdot \alpha$ Ci/g, where α is uranium concentration in ore. In this case a greater degree of inactivity of the most NE activity disposals compared with ores should be noted, which is the result of natural activity vitrification in melt.

Of great importance is practical experience gained in achieving a rather high degree of mixing various radionuclides in the NE produced melt.

The basic features that differ NET for disposal of HLW from the technology of underground nuclear tests are related to disposal of much greater amounts of long-period activity and sometimes to the necessity of solving heat removal problems at the technological explosion preparation stage.

4. Measures Ensuring Safety of Peaceful Nuclear Explosions

Creation of structures in the rock mass and technologies using nuclear explosions should ensure seismic safety of nearby populated areas and exclude people′s getting in the radiation dangerous zone. After the created structures or technologies have been put into operation, radioactive waste should be confined within rock masses.

As compared with test site explosions, peaceful nuclear explosions had some specific features in terms of the measures ensuring seismic and radiation safety.

First, almost all of them were conducted in wells. Second, they had a field character even if there was a set of explosions, that is there was no stationary base and local personnel for monitoring and ensuring safety, at least before mastering the explosion produced facilities. Third, they were made in various landscape and geological conditions (as opposed to test sites), which required strictly individual approaches to each explosion. Finally, peaceful nuclear explosions meant a direct contact with the local inhabitants, which set one solving concrete social problems.

Seismic safety measures were developed based on the scientifically grounded prediction of seismic parameters and their effects upon people, buildings and structures. The number and scope of the necessary measures in the explosion area were determined according to the predicted seismic intensity.

Technical seismic safety measures included design analysis and additional strengthening of the buildings getting in the area of heavy seismic vibrations, engineering protection of equipment from seismic effects, disassembly and evacuation of most valuable instruments and devices, temporary shutdown of operating plants.

In case of damage, repair operations were performed, for which purpose the reserve of construction materials had been prepared and repair teams had been formed beforehand. To find out whether prediction estimations would agree with the actual results and to collect scientific and statistical data, a network of seismic measurement points was organized.

The problem of seismic safety was rather easily solved by appropriate selection of the distance from the explosion point to the populated areas, taking people out of their houses for a short time (if necessary) and minor repair of damaged buildings (if it took place), while radiation safety ensuring was a challenge even for camouflet explosions.

The system of radiation safety ensuring was a single complex of purposeful interrelated organizational and technical protection and control measures which included planning of measures, their performance at all technological process stages and which were designed both for a normal technological process and abnormal situations. Radiation safety ensuring was under a strict control of sanitary and local bodies.

During operation of structures and technologies radiation manifestations were allowed that caused no personnel exposure to the doses exceeding the permissible standards. The products based on such technologies had to meet the norms for the products, raw materials and other items consumed by the population.

The problem of radiation protection in using nuclear explosions for peaceful purposes is a problem of low doses. The following three fundamental factors form its basis:

- application of a rock mass as the main protection barrier and activity stop;
- application of special nuclear devices producing minimum biologically dangerous radionuclides;
- controllability of the technology by the radiation danger factor.

The radiation safety was provided at all the stages comprising life cycles of the facilities created with nuclear explosions: during their construction, mastering, operation and isolation. It consisted of the following components:

1. Selection of the explosive device to fit the specific aim and conditions providing the lowest contamination of entrails and products.
2. Development of special stemming systems ensuring safety and efficiency of subsequent operations for the whole range of explosion aims and conditions.
3. Selection of the nuclear device loading depth precluding emergence of explosion products in a free water exchange area.
4. Radiation monitoring of the radiation situation and exposure doses.
5. Development of specific emergency scenarios for each explosion and establishment of appropriate sanitary protection zones.

6. Creation and staffing of the special field radiation safety service, construction of special temporary structures at technological sites or close to them such as laboratories, communications, decontamination centers, points of notification, individual radiation monitoring and sanitary protection zone guard.

All the measures and means were intended for two types of situations: a standard situation providing for no emergence of radioactive products on the surface and abnormal situations of various categories. The standard pattern and schedule of activities to be performed by the radiation safety service under field conditions of peaceful nuclear explosions included:

- arrangement and early actuation of the remote gamma radiation dose measurement system on the end box head, on the technological site territory and, if necessary, on the sanitary protection zone border;
- arrangement and early actuation of the continuous gamma radiation dose rate recording instrumentation and air-filtering facilities on the leeward and in the nearest populated areas, arrangement of fallout registers in the sanitary-protection and monitored areas and in the nearest settlements;
- arrangement of radiation monitoring stations on the sanitary protection zone border and in the nearest settlements;
- providing of the personnel involved in the explosion and studies with individual radiation monitoring and individual protection means;
- readiness of the decontamination center for abnormal situations;
- arrival of the radiation patrols equipped with mobile and portable instrumentation for radiation monitoring and sampling at the sanitary protection zone and technological site after the explosion and the first remote measurements have been made ;
- readiness of mobile radiochemical, radiometric, gas laboratories for analysis of express environmental samples;
- readiness of the transport service for immediate (on emergency) personnel evacuation from the control and observation posts.

After the explosion, a joint radiation safety service of the facility Customer and specialized institutions of the Ministry of Medium Machine Building such as VNII of Industrial Technology and (or) the Radium Institute was created. Its aim was to ensure safety of continuos operations according to the standard pattern approved for radiation dangerous facilities.

Opening up of the central area and construction of the industrial site were accompanied by the following radiation safety measures:

- application of a specially designed stemming system that allowed the cavity opening and entrance without carrying radiation products onto the surface;
- if necessary, application of special equipment preventing from release of radionuclides during opening;
- taking of special individual personnel protection measures in case of unexpected release of radioactive products;
- radiation monitoring.

Operation of the facilities was accompanied by the following radiation safety measures:

- application of special nuclear devices for disposal of radioactive products that allowed the amount of radionuclides in the extracted products to be reduced;
- producing of special technological effects on the facility that made it possible to limit carrying of radioactive substances with products (control over hydrodynamic flows during oil extraction intensification, prevention from release of radionuclides from reservoirs with contaminated brine, etc.);
- application of preventive radiation monitoring to avert carrying of radionuclides with extracted products.

During isolation of the facility radiation safety was provided as follows:

- recultivation and decontamination of the territory, disposal of radioactive waste;
- organization of the sanitary protection zone having the appropriate system of restrictive measures.

For survival purposes technological sites at the facility were provided with service buildings, mechanisms and equipment. Besides, there was a settlement for those participating in these activities as well as guard subdivisions having rooms for consumer and medical services.

Reusable buildings were generally installed at the sites.

An important element of the nuclear device loading process was sealing (stemming) of a borehole or a tunnel, for which purpose a “stemming system” was erected in it. The technology of erecting stemming systems was mainly based on the experience and materials available in the industry that were in particular used for fixing oil and gas wells. In some cases unconventional approaches were used that together with specially designed dropping pillars provided entrance to the cavity or the explosion affected area with minimum labor efforts, minimum contamination of the equipment, the environment and minimum personnel exposure risk. The boreholes were filled with mixtures using standard cementing units and machines.

Control over compliance with radiation safety and environment conservation standards and regulations during peaceful nuclear explosions was provided by the bodies and representatives of the Ministry of Public Health, the Sanitary and Epidemiological Control Committee and the State Committee of Hydrometeorology. During implementation of the Program of peaceful nuclear explosions there were neither personnel exposure events nor exposure of the population to the doses exceeding the permissible standards.

5. Peaceful Nuclear Explosions and the Comprehensive Test Ban Treaty

Peaceful nuclear explosions in the Soviet Union were conducted within a large-scale program of activities in the national economy interests. The possibility of using nuclear explosions for peaceful purposes gained international recognition and this fact was stated in the Treaty of 1968 on non-proliferation of nuclear weapons. The text of this treaty emphasizes that a voluntary refusal of states to make and acquire nuclear weapons shall not impede their opportunity to use capabilities of peaceful nuclear explosions.

Currently, the attitude of the international community to peaceful nuclear explosions has changed greatly. There are some reasons for that.

First, in the practice of international cooperation no peaceful nuclear explosions were conducted in the interests of non-nuclear states according to the possibilities specified in the non-proliferation Treaty.

Second, complete development of the technology for making some nuclear explosions including peaceful ones was sometimes related to partial release of radioactive products into the environment. On the one hand, this required improvement of the technology and on the other, contributed into hostile opinions of the public of nuclear explosions in general and of peaceful nuclear explosions (PNE) in particular.

Third, the U.S. program of peaceful nuclear explosions turned out to be rather small in volume (27 PNE, ~2.6% of the total number of nuclear tests) and modest in its results. In 1973 it was stopped. The Soviet Union performed a larger scope of activities of this kind (124 PNE, ~17.3% of the total number of nuclear tests) and its program was in progress till 1988.

The Comprehensive Test Ban Treaty, CTBT that was concluded in autumn of 1996 and has been signed by most states by now prohibits tests of nuclear weapons or any other nuclear explosions.

At the same time, Clause VIII of the Treaty provides for holding conferences every ten years to consider its effects. Such a conference may approve a treaty amendment introduced by recommendation of any treaty member provided it gets common support. This amendment could allow peaceful nuclear explosions (PNC), but with no military benefits from such explosions.

Thus, to show advantages of CTBT, especially to implement it, a thorough substantiation should be given at the state level and the project should be submitted to the international community for its examination. Using IAEA institutional capabilities and duties, it could be possible to bring the CTBT members′ attention to making a legal technological experiment, for example, under the aegis of IAEA and under international control.

The matters of guarantees of the unused peaceful nuclear explosions for solution of parallel military problems may be convincingly settled. To this end, it might be sufficient to agree that peaceful nuclear explosions will be conducted by not individual nuclear states, but by the international body representing the interests of all nuclear states in providing control over such explosions. In this case, the absence of military actions will be guaranteed if consensus is achieved between all nuclear states on each specific technological explosion. At the same time, such a control will be in agreement with the guaranteed non-proliferation of nuclear weapons.

The most delicate matter related to the used nuclear explosive devices may be settled in the following way:

- the nuclear state making a technological explosion submits complete information to the supervising international body of nuclear states and provides it with all kinds of access to the used explosive device, which must be sufficient to guarantee that no military tasks are fulfilled in the experiment (it stands to reason that a scientific and technical appearance of the specific explosive device should meet these conditions);
- nuclear devices for technological explosions are specially designed by the collective body composed of representatives from all nuclear states, which guarantees no possibilities for applying them in the interests of one nuclear state and provides a joint international control over military interests.

Such an approach also allows effective solution of international examination problems that are related to ecological safety of technological explosions and international control over ecological safety during and after technological explosions. Non-nuclear states can be actively involved in discussion of the experiment objectives, conditions of experimenting, inspections at the experiment preparation stage, ecological examinations and ecological monitoring, that is in the whole set of the activities directly not connected with the technological explosive device. Representatives of nuclear states should provide control over non-military application of the technological explosive device. Then the non-proliferation guarantees will be fulfilled completely.

It should be taken into account that the supervising representatives of nuclear states may be competent technical specialists provisionally delegated to the International supervising body that will include representatives of the third countries too. In this case, a legal conclusion on the absence of military purpose will be the conclusion of the international body based on the analysis made by its own experts.

It should be noted that even at the beginning of negotiations on banning nuclear tests the problem of peaceful nuclear explosions was also discussed. In particular, in 1958 the United States suggested the Soviet Union that the Supervising Commission on banning nuclear tests should be authorized to make inspections and to give permission for peaceful nuclear explosions. To eliminate the possibility of using "peaceful" nuclear devices for development of nuclear weapons, the specialists from the American laboratories offered a few different variants:

- construction of the international storage facility for nuclear devices where nuclear states can place nuclear devices designed for peaceful purposes;
- application of the American nuclear devices when "peaceful" explosions are conducted by the Soviet Union and vice versa;
- peaceful nuclear explosions under UN control without measuring characteristics of nuclear devices.

During comprehensive test ban negotiations (1994-1996) only China stood up for leaving peaceful nuclear explosions in the Treaty text, but in July of 1996 it agreed to withdraw this proposal to expedite CTBT conclusion. It admitted that at the next CTBT conferences (in 10 years) it would be possible to raise this question again.

Appendix 1. Soviet Peaceful Nuclear Explosions. Application of Nuclear Explosive Technologies For The National Economy Interests

Starting in 1965, the Soviet Union implemented an extensive program of nuclear explosions for the national economy interests. Since 117 technological explosions from 124 peaceful nuclear explosions were made beyond nuclear test sites, the appended table chronologizes all nuclear explosions conducted in the national economy interests (except for the tests aimed at complete development of industrial nuclear devices that were carried out at nuclear test sites). All peaceful nuclear explosions were conducted under ground. Therefore, they may be classified as underground nuclear explosions for peaceful purposes.

Soviet Peaceful Nuclear Explosions

	Date	Location	Type	Yield, kt	Depth, m	Comments
1965						
1	01/15/65	STS	Chagan shaft 1004	140	178	First industrial nuclear explosion; development of nuclear excavation technology
2	03/30/65	Bashkir ASSR, RSFSR	Butan-1 shaft 617 Butan-1 shaft 618	2.3 2.3	1341	First simultaneous nuclear detonations in two shafts; first oil stimulation experiment
3	06/10/65	Bashkir ASSR, RSFSR	Butan-1 shaft 622	7.6	1350	Oil stimulation experiment
4	10/14/65	STS	Sary-Uzen shaft 1003	1.1	48	Excavation nuclear explosion
1966						
5	04/22/66	Azgir, Kazakh SSR	shaft A-I	1.1	161	First nuclear explosion at Azgir to form cavities in salt
6	09/30/66	Urta-Bulak, Uzbek SSR	shaft 1-s	30	1532	Elimination of a runaway gas well
1967						
7	10/06/67	Tyumen' region, RSFSR	Tavda shaft	0.3	172	Construction of underground cavities
1968						
8	05/21/68	Pamuk, Uzbek SSR	shaft	47	2440	Elimination of a runaway gas well
9	07/01/68	Azgir, Kazakh SSR	shaft A-II	27	600	Experiment to form cavities in salt
10	10/21/68	STS	Tel'kem shaft 2308	0.24	31.4	Excavation nuclear explosion
11	11/12/68	STS	Tel'kem-2 shaft 2305 Tel'kem-2 shaft 2306 Tel'kem-2 shaft 2307	0.24 0.24 0.24	31.4 31.4 31.4	Simultaneous excavation nuclear explosion
1969						
12	09/02/69	Perm' region, RSFSR	Grifon shaft 1001	7.6	1212	Oil stimulation experiment
13	09/08/69	Perm' region, RSFSR	Grifon shaft 1002	7.6	1208	Oil stimulation experiment
14	09/26/69	Takhta-Kugulta, Stavropol' territory, RSFSR	shaft	10	712	Gas stimulation experiment
15	12/06/69	Mangyshlak, Kazakh SSR	shaft 2T	30	407	Development of industrial nuclear explosive technology

	Date	Location	Type	Yield, kt	Depth, m	Comments
1970						
16	06/25/70	Orenburg region, RSFSR	Magistral shaft 1T-2S	2.3	702	Construction of underground cavities
17	12/12/70	Mangyshlak, Kazakh SSR	shaft 6T	80	470	Development of industrial nuclear explosive technology
18	12/23/70	Mangyshlak, Kazakh SSR	shaft 1T	75	497	Development of industrial nuclear explosive technology
1971						
19	03/23/71	Perm’ region, RSFSR	Taiga shaft 1B shaft 2B shaft 3B	15 15 15	128 128 128	Excavation nuclear explosion
20	04/09/71	STS	tunnel 148/1	0.23		Radioactivity transfer experiment
21	07/02/71	Komi ASSR, RSFSR	Globus shaft GB-4	2.3	542	Seismic probing explosion
22	07/10/71	Komi ASSR, RSFSR	Globus shaft GB-3	2.3	465	Seismic probing explosion
23	09/19/71	Ivanovo region, RSFSR	Globus shaft GB-1	2.3	610	Seismic probing explosion
24	10/04/71	Arkhangelsk region, RSFSR	Globus shaft GB-2	2.3	595	Seismic probing explosion
25	10/22/71	Orenburg region, RSFSR	Sapfir shaft E-2	15	1140	Construction of underground cavities
26	12/22/71	Azgir, Kazakh SSR	shaft A-III	64	986	Experiment to form cavities in salt
1972						
27	04/11/72	Mary region, Turkmen SSR	Crater shaft	15	1720	Elimination of a runaway gas well
28	07/09/72	Ukrainian SSR	Fakel shaft	3.8	2483	Elimination of a runaway gas well
29	08/20/72	Kazakh SSR	Region shaft R-3	6.6	489	Seismic probing explosion
30	09/04/72	Murmansk region, RSFSR	Dnepr-1 tunnel	2.1	131	First nuclear explosion on ore fragmentation technology testing
31	09/21/72	Orenburg region	Region shaft R-1	2.3	485	Seismic probing explosion
32	10/03/72	Kalmyk ASSR, RSFSR	Region shaft R-4	6.6	485	Seismic probing explosion
33	11/24/72	Orenburg region, RSFSR	Region shaft R-2	2.3	675	Seismic probing explosion
34	11/24/72	Kazakh SSR	Region shaft R-5	6.6	423	Seismic probing explosion
1973						
35	08/15/73	Kazakh SSR	Meridian shaft MN-3	6.3	600	Seismic probing explosion
36	08/28/73	Kazakh SSR	Meridian shaft MN-1	6.3	395	Seismic probing explosion
37	09/19/73	Kazakh SSR	Meridian shaft MN-2	6.3	615	Seismic probing explosion
38	09/30/73	Orenburg region, RSFSR	Sapfir shaft E-3	10	1145	Construction of underground cavities
39	10/26/73	Bashkir ASSR, RSFSR	Kama-2 shaft	10	2026	Technology for the burial of petroleum chemical industrial wastes

	Date	Location	Type	Yield, kt	Depth, m	Comments
1974						
40	07/08/74	Bashkir ASSR, RSFSR	Kama-1 shaft	10	2123	Technology for the burial of petroleum chemical industrial wastes
41	08/14/74	Tyumen' region, RSFSR	Gorizont shaft G-2	7.6	534	Seismic probing explosion
42	08/29/74	Komi ASSR, RSFSR	Gorizont shaft G-1	7.6	583	Seismic probing explosion
43	10/02/74	Yakut ASSR, RSFSR	Kristall shaft	1.7	98	Development of dam construction technology
44	12/07/74	STS	Lazurit shaft R-1	1.7	75	Development of dam construction technology
45	12/16/74	STS	tunnel 148/5	3.8		Radioactivity transfer experiment
1975						
46	04/25/75	Azgir, Kazakh SSR	shaft A-II-2	0.35	600	Explosion in a cavity in salt formed by a previous explosion
47	08/12/75	Yakut ASSR, RSFSR	Gorizont shaft G-4	7.6	496	Seismic probing explosion
48	09/29/75	Krasnoyarsk territory, RSFSR	Gorizont shaft G-3	7.6	834	Seismic probing explosion
1976						
49	03/29/76	Azgir, Kazakh SSR	shaft A-III-2	10	986	Explosion in a cavity in salt formed by a previous explosion
50	07/29/76	Azgir, Kazakh SSR	shaft A-IV	58	1000	Experiment to form cavities in salt
51	11/05/76	Yakut ASSR, RSFSR	Oka shaft 42	15	1522	Oil stimulation experiment
1977						
52	07/26/77	Krasnoyarsk territory, RSFSR	Meteorit shaft M2	15	850	Seismic probing explosion
53	08/11/77	Chita region, RSFSR	Meteorit shaft M5	8.5	494	Seismic probing explosion
54	08/21/77	Krasnoyarsk territory, RSFSR	Meteorit shaft M3	8.5	600	Seismic probing explosion
55	09/10/77	Irkutsk region, RSFSR	Meteorit shaft M4	7.6	550	Seismic probing explosion
56	09/30/77	Azgir, Kazakh SSR	shaft A-V	10	1500	Experiment to form cavities in salt
57	10/14/77	Azgir, Kazakh SSR	shaft A-II-3	0.1	600	Explosion in a cavity in salt formed by a previous explosion
58	10/30/77	Azgir, Kazakh SSR	shaft A-II-4	0.01	600	Explosion in a cavity in salt formed by a previous explosion
1978						
59	08/09/78	Yakut ASSR, RSFSR	Kraton shaft KR-4	22	567	Seismic probing explosion
60	08/24/78	Yakut ASSR, RSFSR	Kraton shaft KR-3	22	577	Seismic probing explosion
61	09/12/78	Azgir, Kazakh SSR	shaft A-II-5	0.08	600	Explosion in a cavity in salt formed by a previous explosion
62	09/21/78	Krasnoyarsk territory, RSFSR	Kraton shaft KR-2	15	886	Seismic probing explosion
63	10/08/78	Yakut ASSR RSFSR	Vyatka shaft 43	15	1545	Oil stimulation experiment

	Date	Location	Type	Yield, kt	Depth, m	Comments
64	10/17/78	Azgir, Kazakh SSR	shaft A-VII shaft A-VII	20 - 150 0.001 - 20		First simultaneous nuclear detonations at Azgir to form cavities in salt (total energy release - 73 kt)
65	10/17/78	Tyumen' region, RSFSR	Kraton shaft KR-1	22	593	Seismic probing explosion
66	11/30/78	Azgir, Kazakh SSR	shaft A-II-6	0.06	600	Explosion in a cavity in salt formed by a previous explosion
67	12/18/78	Azgir, Kazakh SSR	shaft A-IX	103	630	Experiment to form cavities in salt
1979						
68	01/10/79	Azgir, Kazakh SSR	shaft A-II-7	0.5	600	Explosion in a cavity in salt formed by a previous explosion
69	01/17/79	Azgir, Kazakh SSR	shaft A-VIII shaft A-VIII	0.001 - 20 20 - 150		Simultaneous detonations to form cavities in salt (total energy release - 65 kt)
70	07/14/79	Azgir, Kazakh SSR	shaft A-XI shaft A-XI shaft A-XI	0.001 - 20 0.001 - 20 0.001 - 20		Simultaneous detonations to form cavities in salt (total energy release - 21 kt)
71	08/12/79	Yakut ASSR, RSFSR	Kimberlit shaft KM-4	8.5	982	Seismic probing explosion
72	09/06/79	Krasnoyarsk territory, RSFSR	Kimberlit shaft KM-3	8.5	599	Seismic probing explosion
73	09/16/79	Ukrainian SSR	Klivazh mine	0.3	903	Nuclear explosion in a coal mine to prevent sudden blow-out of methane
74	10/04/79	Tyumen' region, RSFSR	Kimberlit shaft KM-1	22	837	Seismic probing explosion
75	10/08/79	Yakut ASSR, RSFSR	Sheksna shaft 47	15	1545	Oil stimulation experiment
76	10/24/79	Azgir, Kazakh SSR	shaft A-X shaft A-X	0.001 - 20 20 - 150		Simultaneous detonations to form cavities in salt (total energy release - 33 kt)
1980						
77	06/16/80	Bashkir ASSR, RSFSR	Butan-2 shaft 1	3.2	1400	Oil stimulation experiment
78	06/25/80	Bashkir ASSR, RSFSR	Butan shaft 3	3.2	1390	Oil stimulation experiment
79	10/08/80	Astrakhan' region, RSFSR	Vega shaft 1T	8.5	1050	Construction of underground cavities
80	11/01/80	Krasnoyarsk territory, RSFSR	Batolit shaft BT-1	8	720	Seismic probing explosion
81	12/10/80	Tyumen' region, RSFSR	Angara shaft	15	2485	Oil stimulation experiment
1981						
82	05/25/81	Arkhangelsk region, RSFSR	Pirit shaft	37.6	1511	Elimination of a runaway gas well
83	09/02/81	Perm' region, RSFSR	Geliy shaft 401	3.2	2088	Oil stimulation experiment
84	09/26/81	Astrakhan' region, RSFSR	Vega shaft 2T/2	8.5	1050	Construction of underground cavities
85	09/26/81	Astrakhan' region, RSFSR	Vega shaft 4T/2	8.5	1050	Construction of underground cavities
86	10/22/81	Krasnoyarsk territory, RSFSR	Shpat shaft ShP-2	8.5	581	Seismic probing explosion
1982						
87	07/31/82	Irkutsk region, RSFSR	Rift shaft RF-3	8.5	554	Seismic probing explosion

	Date	Location	Type	Yield, kt	Depth, m	Comments
88	09/04/82	Krasnoyarsk territory, RSFSR	Rift shaft RF-1	16	960	Seismic probing explosion
89	09/25/82	Krasnoyarsk territory, RSFSR	Rift shaft RF-4	8.5	554	Seismic probing explosion
90	10/10/82	Yakut ASSR, RSFSR	Neva shaft 66	15	1502	Oil stimulation experiment
91	10/16/82	Astrakhan' region, RSFSR	Vega shaft 3T	13.5	1057	Construction of underground cavities
92	10/16/82	Astrakhan' region, RSFSR	Vega shaft 5T	8.5	1100	Construction of underground cavities
93	10/16/82	Astrakhan' region, RSFSR	Vega shaft 6T	8.5	991	Construction of underground cavities
94	10/16/82	Astrakhan' region, RSFSR	Vega shaft 7T	8.5	947	Construction of underground cavities
1983						
95	07/20/83	Kazakh SSR	Lira shaft 1T	15	907	Construction of underground cavities
96	07/20/83	Kazakh SSR	Lira shaft 2T	15	917	Construction of underground cavities
97	07/20/83	Kazakh SSR	Lira shaft 3T	15	841	Construction of underground cavities
98	09/24/83	Astrakhan' region, RSFSR	Vega shaft 8T	8.5	1050	Construction of underground cavities
99	09/24/83	Astrakhan' region, RSFSR	Vega shaft 9T	8.5	1050	Construction of underground cavities
100	09/24/83	Astrakhan' region, RSFSR	Vega shaft 10T	8.5	950	Construction of underground cavities
101	09/24/83	Astrakhan' region, RSFSR	Vega shaft 11T	8.5	920	Construction of underground cavities
102	09/24/83	Astrakhan' region, RSFSR	Vega shaft 12T	8.5	1100	Construction of underground cavities
103	09/24/83	Astrakhan' region, RSFSR	Vega shaft 13T	8.5	1100	Construction of underground cavities
1984						
104	07/21/84	Kazakh SSR	Lira shaft 4T	15	816	Construction of underground cavities
105	07/21/84	Kazakh SSR	Lira shaft 5T	15	844	Construction of underground cavities
106	07/21/84	Kazakh SSR	Lira shaft 6T	15	955	Construction of underground cavities
107	08/11/84	Komi ASSR, RSFSR	Kvarts shaft K-2	8.5	759	Seismic probing explosion
108	08/25/84	Tyumen' region, RSFSR	Kvarts shaft K-3	8.5	726	Seismic probing explosion
109	08/27/84	Murmansk region, RSFSR	tunnel Dnepr-2 tunnel Dnepr-2	1.7 1.7	175 175	Development of technology for the breakage of ore
110	08/28/84	Perm' region, RSFSR	Geliy shaft 402	3.2	2065	Oil stimulation experiment
111	08/28/84	Perm' region, RSFSR	Geliy shaft 403	3.2	2075	Oil stimulation experiment
112	09/18/84	Kemerovo region, RSFSR	Kvarts shaft K-4	10	557	Seismic probing explosion
113	10/27/84	Astrakhan' region, RSFSR	Vega shaft 14T	3.2	1000	Construction of underground cavities
114	10/27/84	Astrakhan' region, RSFSR	Vega shaft 15T	3.2	1000	Construction of underground cavities
1985						
115	06/18/85	Tyumen' region, RSFSR	Benzol shaft	2.5	2860	Oil stimulation experiment

	Date	Location	Type	Yield, kt	Depth, m	Comments
116	07/19/85	Arkhangelsk region, RSFSR	Agat shaft	8.5	772	Seismic probing explosion
1987						
117	04/19/87	Perm' region, RSFSR	Geliy shaft 404	3.2	2015	Oil stimulation experiment
118	04/19/87	Perm' region, RSFSR	Geliy shaft 405	3.2	2055	Oil stimulation experiment
119	07/07/87	Yakut ASSR, RSFSR	Neva shaft 68	15	1502	Oil stimulation experiment
120	07/24/87	Yakut ASSR, RSFSR	Neva shaft 61	15	1515	Oil stimulation experiment
121	08/12/87	Yakut ASSR, RSFSR	Neva shaft 101	3.2	815	Oil stimulation experiment
122	10/03/87	Kazakh SSR	Batolit shaft BT-2	8.5	1002	Seismic probing explosion
1988						
123	08/22/88	Tyumen' region, RSFSR	Rubin shaft RN-2	15	829	Seismic probing explosion
124	09/06/88	Arkhangelsk region, RSFSR	Rubin shaft RN-1	8.5	820	Seismic probing explosion

Chapter 7

The 1974 Threshold Test Ban Treaty and the 1996 Comprehensive Test Ban Treaty

Content

1. Negotiation Process to Limit Nuclear Testing

1.1. First Steps Toward Limitation of Nuclear Testing

To analyze international agreements on limiting nuclear tests, one should start with the moratorium on the USSR and U.S. nuclear tests from November 3, 1958 till September 1, 1961 terminated as the result of rapid deterioration of relations between the two states. That was the very event underlying the new political tradition, i.e., embarking upon a state policy in the area of nuclear tests as a sui generis indicator of general relationship between the Soviet Union and the United States.

By the onset of the moratorium, the United States had been essentially ahead of the Soviet Union in the development of its nuclear program. The nuclear test practice in the United States has numbered 13 years as against 9-year nuclear tests efforts in the Soviet Union. By that time in the United States, 196 tests had been conducted with 83 ones having been conducted in the Soviet Union. Concurrently, the dynamics of the nuclear tests number was of no benefit to the United States: while in 1955, the United States was 2.9 times ahead of the Soviet Union in terms of nuclear tests number, by 1959 – 2.35 times. Not only this quantitative gap in gaining experimental skills of nuclear weapons development should be kept in mind but rather definite U.S. superiority in the development of computing equipment, playing a major role in the physical and mathematical modeling system (PMMS) and technologies driving the development of diagnostic means for nuclear weapons detonation.

By 1958, using the designs developed, the United States had created a huge nuclear weapons stockpile involving the overall number of ~ 7300 nuclear devices with the total megatonnage of 17.5 Mt. No nuclear stockpile, whose characteristics were somewhat comparable with the abovementioned, was available in the Soviet Union at that time.

Though the real reasons for the U.S. moratorium are not known to us, objectively it was directed toward ensuring American domination in the nuclear device (ND) development efforts and its further strengthening based on the advances in technological benefits.

Politicians discovered a new area of propaganda for themselves when “peaceful disposition and the degree of responsibility under the conditions of confrontation” were related to the attitude towards nuclear tests, their limitation or cessation. The myths were invented about the necessity to comprehensively prohibit nuclear weapons as the primary condition for creating the safe world and about the nuclear weapons test ban as a crucial step in this direction. Decades thereafter, the nuclear weapons alone are evident to have deterred the humankind from World War III in the XX-th century in the environment of civilization's antagonistic splitting into "the communist world" and "the free world". To refrain from thousand-year's stereotypes of behavior, a drastic remedy was needed, i.e., the threat of inevitable devastation combined with the rigid order of the militarized power structure.

Since nuclear weapons tests, in terms of science and technology, are a kind of physical experiment and an integral part of the technology for creating ND, their cessation had a major impact on the situation involving nuclear weapons development. As it was mentioned above, starting from a certain level of ND development, nuclear tests offer no tight control over development and production of nuclear weapons. To a great extent, they can be substituted by PMMSs of ND operation, conservation of production technologies and reduced ND-related requirements. In this sense, the cessation of nuclear testing does not govern the nuclear disarmament process. However, the said cessation destroys the technological process of ND development existing in testing conditions, calls for its transformation and adaptation to new conditions.

It is of interest to mention that the nuclear testing cessation was always regarded in the Soviet Union to be a temporary measure, political games. The development of such an attitude was affected to a certain extent by an unexpected declaration of moratoria, the lack of the governmental program for arranging nuclear weapons for cessation of tests and for moratorium-period operations. For instance, no task has been ever set at the governmental level to develop a part of a nuclear device, whose production and re-production could be possible without nuclear testing for a long period. This problem was, for sure, solved to a certain extent but its addressing was incidental, of secondary importance.

On the whole, the effect of the first moratorium on nuclear testing brought about diverse and profound consequences. In politics, a number of new stereotypes of behavior were developed, new components of peacemaking mythology were created. The novel aspect emerged in the ND development, i.e., with nuclear weapons being of crucial importance for ensuring defense-capabilities and actual deterrence, political opportunities to reject weapons testing were demonstrated. At the same time, in an implicit form such an approach presumed the availability of sufficient safeguards of nuclear weapons reliability and a high degree of confidence in them.

1.2. The 1963 Limited Test Ban Treaty

In August 1963, the Soviet Union, the United States and the United Kingdom of Great Britain signed the Limited Test Ban Treaty that prohibited nuclear explosions in the atmosphere, space and underwater and allowed only those conducted underground.

As an official international agreement, the status of this Treaty is special as compared with a moratorium being in essence an internal state act. The politicians demonstrated a capability in principal of concluding international agreements to control nuclear weapons; the nuclear powers rejected to use the planetary atmosphere as a vessel to dilute the explosion-generated radioactivity; the experimental verification techniques were considerably modified.

By the time of signing the Treaty, the United States had conducted 333 nuclear tests and the Soviet Union - 221 ones conducting more nuclear tests for 1961-1962 than for the entire period preceding the moratorium of 1958. Though for the period between the end of the moratorium and the Treaty's (1963) coming into force the United States conducted as many nuclear tests as did the Soviet Union, the situation changed considerably as compared with that at the beginning of the moratorium of 1958. Evidently, that was one of the reasons for the Treaty of 1963 not to provide for the prohibition of all nuclear weapons tests. The situation concerning the nuclear weapons development could hardly satisfy the United States seeking to take a step towards changing the balance of forces, i.e., to deploy multiple independent re-entry vehicles with novel ND types assuming new tests required. On the other hand, for the Soviet Union the cessation of aboveground tests meant the elimination of the area developing super-yield NDs and creation of additional obstacles as compared with the United States due to more sophisticated testing techniques. The fact that the United States had better prepared for the transition to underground tests was proved by the evidence of their having conducted 116 underground nuclear tests by the time of the Treaty's (1963) coming into force with only 2 nuclear tests of this type having been conducted in the Soviet Union.

Nevertheless, the transition to underground tests was acceptable in principle for the USSR as well whose specialists developed basic components for the new testing system fairly rapidly. Irrespective of importance evaluation of particular aspects of the Treaty (1963), its general humanitarian nature is evident, since the Treaty stopped arbitrary propagation of nuclear explosion-produced radioactivity throughout the planetary space confining its presence to the territory of nuclear powers. Concurrently, such an approach made the issue of conducting nuclear tests to be, in essence, a prerogative of the nuclear power itself.

1.3. The 1972 Anti-Ballistic Missile Treaty (ABM Treaty)

The next agreement playing an essential role in nuclear tests limitation became the Treaty of 1972 between the Soviet Union and the United States on the limitation of anti-ballistic missile systems (ABM Treaty). The changed role of strategic delivery systems, having pushed into the foreground ballistic missiles on land and sea being equipped with multiple independent re-entry vehicles rather than the strategic aviation, was accompanied by research intensification in the area of anti-ballistic missile systems and measures. Though nuclear weapons offered diverse ways to efficiently affect both the stages of missiles in the active path section and warheads after their separation the issue of possible development of the efficient anti-missile system seemed to be next to an intractable problem. Such an attitude was governed by a huge number of would-be AMS targets (due to the increased number of ballistic missiles, warheads and the lack of limitations for them), by the problem of identifying objects being destroyed in the target structure with relatively small time and space resources for interception and the requirements for high efficiency of ABM systems in each separate case of interception conditioned by huge damages caused by each target missed. Taking into account the U.S. overall supremacy especially in the areas of high tech and fine tech playing a specific role in the development of ABM systems, it was quite acceptable for the USSR to conclude the ABM treaty, which released it from the military-technology competition in the field unfavorable for it. On the other hand, the U.S. specialists had apparently realized that in the conditions of the evident arms race any money invested and efforts taken to develop ABMs could be brought to nothing with lower costs by developing strategic offensive arms. The conclusion of the ABM Treaty definitely allowed the reduction of major nuclear testing programs with the view of developing ABM systems whose implementation would have been otherwise inevitable irrespective of the ultimate result, i.e., the creation of the efficient ABM system.

At the same time the ABM issue one more time gave rise to the researches in the area of nuclear weapon effects and its tenacity thus directly affecting the nuclear testing program.

Concurrently with the Anti-Ballistic Missile Treaty of 1972, the Interim Agreement on certain limitation measures in the field of strategic missile launchers was signed. This agreement imposed limitations on the possibility of increasing the number of silo-based BMs as well as on the growth of the SLPM. Later on this agreement was developed in the provisions of SALT II.

1.4. Development of Nuclear Weapons and Nuclear Testing in 1963-1976

It is of interest to compare the dynamics of conducting tests in the Soviet Union and the United States during the period of 1963-1976, from the moment of coming into effect of the Limited Nuclear Test Ban Treaty in August 1963 through 1976 when the provisions of the Treaty of 1974 on limiting underground tests to the ≤ 150 kt energy yield came into force. Simultaneously, the Soviet Union had terminated all nuclear tests (NT) staring from *Å* > 150 since 1976 and the United States- after March 31, 1976 in compliance with the provisions of the Treaty.

Table 7.1 presents the total number of all nuclear tests conducted by the Soviet Union and the United States (N_{NT}) as well as the total number of detonations of all nuclear NDs for the period under consideration by years. N_{NT} and N_{ND} differ due to the fact that a number of NTs are represented by the totality of several ND detonations. The techniques of conducting NT with the detonation of several nuclear NDs was considerably developed in the Soviet Union and allowed it to bridge, to a great extent, the original technological gap in underground testing between the Soviet Union and the United States.

The great emphasis was placed at that time on the efforts involving nuclear explosions for civilian purposes to address a variety of industrial problems. Some nuclear explosions (NEs) for civilian purposes also involved the detonation of a number of nuclear devices, i.e., featured a pattern-shot nature. The data of table 7.1 involve the overall totality of nuclear explosions.

Table 7.1

Dynamics of the total numbers of nuclear explosions for civilian purposes, detonation of nuclear warheads and devices by the USSR and the U.S. in 1963-1976

	Year	1963	1964	1965	1966	1967	1968	1969	1970
USSR	N_{NT}	0	9	14	18	17	17	19	16
	N_{ND}	0	9	15	19	23	23	24	21
U.S.	N_{NT}	18	47	39	48	42	56	46	39
	N_{ND}	20	50	40	49	42	72	61	60
	Year	1971	1972	1973	1974	1975	1976	Total	
USSR	N_{NT}	23	24	17	21	19	21	235	
	N_{ND}	29	31	22	27	35	27	305	
USA	N_{NT}	24	27	24	23	22	21	476	
	N_{ND}	28	32	27	26	23	21	551	

It is seen from table 7.1 that during the period under consideration the United States conducted 476 nuclear tests and nuclear explosions for civilian purposes detonating 551 nuclear devices. The Soviet Union conducted 235 nuclear tests and nuclear explosions for civilian purposes detonating 305 nuclear devices during that period. Hence, the United States, as against the Soviet Union, conducted by a factor of ~ 2 NTs more and detonated ~ 1.8 times more NDs during that period.

For more accurate comparisons of Soviet and U.S. nuclear weapons testing programs, table 7.2 presents the values of N_{NT} and N_{ND} without NTs and NDs related to the joint tests conducted in conjunction with the United Kingdom at the Nevada test site.

According to data from table 7.2, during the period under consideration, less detonations of NDs for civilian purposes, the United States conducted 448 NTs detonating 515 nuclear devices with the Soviet Union conducting 184 NTs detonating 249 nuclear devices. Hence, the United States exceeded the Soviet Union 2.43 times in the number of NTs and 2.07 times in the number of the detonated nuclear devices.

According to data from table 7.2, the period under consideration is divided into two stages: from 1963 through1970 and from 1971 through 1976. During the first period, the United States was a factor of 3.4-3.2 and during the second period a factor of 1.5-1.1 ahead of the Soviet Union in the numbers of NTs conducted and NDs denoted. This variation in the two periods was primarily due to the reduced intensity of NTs conducted by the United States.

Table 7.2

Dynamics of nuclear tests and nuclear explosions in the Soviet Union and the United States in 1963-1976

	Year	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	Total
USSR	N_{NT}	0	9	10	16	16	13	15	13	15	16	12	15	16	18	184
	N_{ND}	0	9	10	17	22	17	20	18	19	23	17	21	32	24	249
U.S.	N_{NT}	17	39	37	44	39	52	45	38	23	27	23	22	22	20	448
	N_{ND}	19	42	38	45	39	64	60	57	27	32	24	25	23	20	515

1.5. Programs of Underground Testing of High-Yield Nuclear Devices

Since the Treaty of 1974 places limits on nuclear testing yield, the data on characteristics of high-yield nuclear tests conducted by the Soviet Union and the United States are of interest. As such NTs we have selected explosions of nuclear devices whose energy-yield is not less than 200 kt. This threshold is conditioned by the availability of relevant information in the official U.S. DOE’s publications. Table 7.3 presents the annual distribution of the numbers of high-yield nuclear device detonations (nuclear devices involved in pattern-shot NTs included) for the Soviet Union and the United States.

Table 7.3

Dynamics of high-yield nuclear device explosions conducted by the Soviet Union and the United States in 1963-1976

Year	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	Σ
USSR	0	0	0	2	0	0	2	3	3	3	5	3	10	0	31
U.S.	1	0	0	2	1	3	3	2	1	0	1	0	5	7	26

It is seen from table 7.3 that the situation with high-yield nuclear explosions is essentially different from the entire situation with conducting nuclear device explosions (tables 7.1 and 7.2). During the period under consideration, the United States conducted 26 explosions of nuclear devices of the said category, with the Soviet Union conducting 31 detonations of nuclear devices of this class. The total energy released during the explosions conducted by the United States can be estimated as 21-22 Mt, actually coinciding with total energy released by the USSR’s explosions of this category, i.e. 21.5 Mt.

This fact also specified the approximate equality of the overall megatonnage of all NTs conducted by the Soviet Union (27.3 Mt) and the United States (32 Mt) during the period under consideration in spite of almost the twofold difference in the total number of detonated nuclear devices detonated. Let us also note that, less the energy release of the detonated high-yield nuclear devices (NDs), the total energy release of the rest ND explosions (10.5 Mt for the United States and 5.8 Mt for the Soviet Union) was approximately proportional to the number of the detonated devices.

It is essential to note that with the approximate equality of the scopes of programs on conducting high-yield explosions in the Soviet Union and the United States, their implementation techniques offered substantial differences. For instance, all U.S. 26 high-yield nuclear explosions (NE) were individual tests in the boreholes. At the same time, of the USSR’s 31 high-yield NEs, 26 explosions were conducted in the tunnels and 5 in the boreholes. Such a peculiarity was specified by different capabilities of the Nevada and the Novaya Zemlya test sites. Among the U.S. 26 high-yield NEs, 23 NEs were conducted at the Nevada test site, 2 NEs on the island

Amchitka and one NE in North Nevada. All the USSR’s 31 high-yield NEs were conducted at the Novaya Zemlya test site

Hence, with the essential overall U.S. superiority in conducting NTs during the said period, we can state parity in conducting high-yield-category nuclear explosions. That parity was also maintained during a year prior to the Treaty’s coming into force. During the period from 1974 till the time of the Treaty’s (March 31, 1976) coming into effect, the Soviet Union conducted 13 high-yield nuclear explosions, with the United States conducting 12 explosions of this class.

While analyzing the Treaty (1974)- related issues it is necessary to take into consideration that high-yield NEs were, for sure, a heavy burden imposed on the Nevada test site. The USSR’s situation in this respect was more favorable since the Novaya Zemlya test site was far away from residential areas

2. The Threshold Test Ban Treaty of 1974 and the Peaceful Nuclear Explosions Treaty of 1976

2.1. Background of the Treaties

During the years following the conclusion of the Moscow Treaty prohibiting nuclear tests in three media, the tense, protracted and strained negotiations on prohibiting underground nuclear explosions were held. The negotiations were primarily conducted within the framework of the Committee on Disarmament originally including 18 countries. The Committee started its work in March 1962. In 1969, the Committee was extended to include 26 members and from 1979 to 1986 - up to 40 members, five nuclear states included. The position of the Soviet Union and its Warsaw Treaty allies did not concur with that of the United States and its NATO allies as regards the control issues, i.e. establishing a procedure for international on-site inspections to verify and identify ambiguous seismic events. The Soviet Union upheld the opinion, according to which the national means for detecting and identifying seismic events ensured due control over the observance of the commitments by the countries concerning the cessation of underground nuclear tests. The United States, the United Kingdom and their NATO allies insisted on establishing the international on-site inspection to identify the nature of ambiguous seismic events. The positions of the parties did not agree on this issue and by the mid- 1960-s the negotiations on this problem had fallen into stagnation.

The improvement of the Soviet-American relations became a major event in the early 1970-s. In 1972 and in 1974, U.S. president Richard Nixon paid a visit to the

Soviet Union and in 1973 L.I.Brezhnev made a trip to the United States. In November 1974, the meeting between L.I.Brezhnev and Gerald Ford, having been elected shortly before that the U.S. president, was held. During the course of the meetings, held between the leaders of the two states, a number of important treaties and agreements on the problems of limiting strategic arms, anti-ballistic missile defense, etc. were concluded. Among these agreements, the Treaty on limiting underground nuclear weapons tests was signed on July 3, 1974. The treaty stipulated to oblige the parties to prohibit, prevent and not to conduct underground tests on nuclear weapons in excess of 150 kt since March 31, 1976. The control over the observance of the terms of the Treaty had to be exercised by each of the parties by using national technologies. The Treaty did not apply to underground nuclear tests for civilian purposes. (The relevant Treaty on them was signed on May 28, 1976). To ensure control, by using the national technologies, the protocol, signed on the same day, envisioned the exchange of data concerning testing sites and nuclear weapons tests conducted and the information on two previous nuclear tests with a view of calibrating seismographic equipment.

The Soviet-American treaty on limiting nuclear weapons tests was an indicator of efforts taken by the two nuclear powers to pave the way for the cessation of all the tests of this kind and of the desire of the Soviet Union and the United States to bolster detente in their relations. It testified to the intents of these states to put an end to the development of high-yield weapons. The Treaty laid the foundation for developing principles of control over the cessation of lower-yield explosions until they were to be completely prohibited.

By March 31, 1976, the Treaty on limiting underground nuclear tests had not been ratified by the United States and the Soviet Union. However, since that date the sides restricted the testing yield to the upper limit of 150 kt. For more than a decade the United States and the Soviet Union employed their means of control to carefully watch each other’s activities at the test sites. Occasionally, seismic signals from nuclear explosions exceeded the norm limits established with calibration. In this case, the diplomats of the U.S. State Department or the Ministry of Foreign Affairs of the Soviet Union started exchanging inquiries, explanations or mere accusations.

Joint Soviet-American nuclear experiments and the following amendments to the treaty’s articles, concerning mutual control over high-power tests, created conditions for the treaty ratification. The Soviet Union ratified the treaty on October 9, 1990, the United States – on December 8, 1990. On December 11, 1990, the exchange of instruments of ratification took place.

2.2. Military and Technological Background for Signing Treaties

By the mid 1970-s, the nuclear weapons (NW) of the United States and the Soviet Union, especially strategic ones, attained a high level both in terms of military-technical characteristics and infrastructure development. The fruits of the technical revolution in material science, radio electronics, computer, rocket and aeronautical engineering found their implementation, in the first place, in new nuclear weapons systems. The substantial accuracy improvement of the warhead delivery systems as well as the development of MIRV-class multi-charge warheads with the enhanced counteracting capability against anti-missile defense started to play an anticipatory role in enhancing the NW efficiency. The effective throw-weight of missiles remained the same or increased inconsiderably, therefore, multi-charge capability was attained due to transition to lighter-weight and small-size warheads. Inter-correlation of such parameters as durability of silo-based launchers of would-be adversary, the accuracy of warhead delivery, the number of warheads and dummy targets for effective overcoming the anti-missile defense led to optimizing the warhead yield.

On the other hand, in the area of developing high-yield nuclear devices a number of problems were successfully resolved in 1961-1962 and new essential advances were made during the period from 1966 through 1975. So, it can be noted that by the time under consideration, the problem involving the development of novel high-yield nuclear devices had not been of top priority any longer in developing NWs in the Soviet Union.

At the same time, the treaty was not to hamper to address the problems of upgrading NDs developed by that time primarily due to improvement of various parameters of primary modules. The limiting energy release level of 150 kt provided such a technological opportunity and the effective use was made of it later on in a variety of small-scale tests.

More challenging problems arose if there was a need for developing novel, fairly high-yield nuclear devices with the energy-release substantially in excess of 150 kt, which could not be implemented as mere upgrading of earlier built nuclear devices. Yet, in this case no insurmountable obstacles emerged either, since the problem of testing novel nuclear devices on small-scale was not a new one for our specialists. Since starting the development of two-stage nuclear WHs (RDS-37; experiment on November 29, 1995) a number of secondary modules had been tested part-yield. Suffice it to say that already back in 1956-1958 in 7 tests the secondary module was tested half-yield, with various techniques being used to reduce the energy release.

While developing novel NDs under NT conditions, involving small-scale energy release, the problem of accurate estimation of the rating energy-release is a matter of importance. This issue often played a major role when a nuclear device was being accepted by a customer or while developing a novel nuclear device on the competitive basis.

2.3. The Subject of the Threshold Test Ban Treaty Between the Soviet Union and the United States

The Treaty was signed in Moscow on July 3, 1974. However, due to U.S. doubts concerning the efficiency of its control capabilities it was not ratified for a long time.

On March 31, 1976, the U.S. State Department declared that they had no plans to conduct high-yield nuclear weapons testing, i.e. in excess of 150 kt, in the nearest future. On April 1976, TASS published a report declaring that the Soviet Union would take no actions inconsistent with the terms of the Treaty (July 3, 1974) provided the United States, on their part, would act in the similar way.

The Treaty includes the preamble, 5 articles and the protocol

According to Article I of the Treaty, since March 31, 1976, the Soviet Union and the United States have entered into commitments to prohibit, prevent and not to conduct any under-ground nuclear weapons tests in excess of 150kt in any place being under their jurisdiction or control. Besides, the sides assumed obligations to limit their underground nuclear tests to minimal amounts.

Article I confirms the intent of both the countries to proceed with the negotiations with the view of resolving the problem of cessation of all underground nuclear weapons tests

In compliance with Article III of the treaty, its terms do not apply to underground nuclear tests for civilian purposes.

The Treaty and the enclosed Protocol provide for the elaborated terms of control over observance of the commitments entered into by the parties of the Treaty.

To ensure the control over observance of the terms of the Treaty, each of the party shall employ available national technologies. The application of control means should meet the generally acknowledged international law and not exceed the bounds of these objectives to the detriment of security and national interests of the sides

The protocol to the Treaty regulates the issues of mutual information exchange concerning nuclear weapons test sites and nuclear weapons tests conducted. It is associated with the fact that a number of natural factors, types of rocks, in which the explosion is conducted, in the first place, affect the operational efficiency and accuracy of teleseismic devices detecting underground explosions and identifying their yield. Therefore, to ensure the needed recording precision for seismic signals, the knowledge of basic geological and geophysical properties of test sites is of importance. The exchange of such data is stipulated by the Protocol.

No sooner than after conducting joint experiments in 1988 on the Nevada test site and the Semipalatinsk test site, the Treaty-related objections were waived and it became effective on December 11, 1990. It should be specifically emphasized that after March 31, 1976, the sides took no actions contradicting the terms of the Treaty, though time and again accused each other of violating the terms of the Treaty.

Let us consider some key definitions as an example.

The term “underground nuclear weapons testing” means ether a single underground nuclear explosion conducted on a test-site, or two or more underground explosions conducted on a test-site within an area delineated by a two-kilometer diameter circle within the overall time period of 0.1 sec. The test yield is the aggregate yield of all explosions involved in this test.

The term “an explosion” means a nuclear energy release from a charging container.

The term “a charging container” means, with respect to each explosion, a container or a casing for one or more explosive nuclear devices.

The test sites for the sides are the Nothern test site (Novaya Zemlya) and the Semipalatinsk test site for the Union of the Soviet Socialist Republics and the Nevada test site for the United States of America.

For the objectives of the Treaty, all underground nuclear explosions on the test sites are regarded as underground nuclear weapons tests and fall within all terms of the Treaty.

With the view of controlling the observance of the Treaty, the controlling side, in addition to employing the available national control technologies, has the right:

à) to accomplish any kind or all kinds of control-related activities involving the application of the hydrodynamic technique for measuring yield of each explosion in the test as regards the test with the targeted yield in excess of 50 kt;

b) to accomplish any kind or all kinds of control-related activities involving the application of the seismic technique for yield measuring as regards the test with the targeted yield in excess of 50 kt;

ñ) to accomplish any kind or all kinds of control-related activities involving the on-site inspection, as regards a test with the targeted yield in excess of 35 kt.

The side conducting a test has the right to conduct a test with the targeted yield in excess of 35 kt in the cavity whose volume exceeds 20000 cubic meters provided the sides have agreed on the measures of control with respect to such a test.

With the view of applying the seismic technique for yield measuring, the controlling side has the right to perform independent seismic measurements on three allocated seismic stations in the territory of the Side conducting the experiment.

2.4. The Subject of the Peaceful Nuclear Explosions Treaty Between the Soviet Union and the United States

The Treaty was signed on May 28, 1976, in Moscow and in Washington. However, due to U.S. doubts concerning the efficiency of its control capabilities it was not ratified for a long period.

The Treaty includes the preamble, nine articles and the protocol.

The preamble emphasizes that the sides confirm their adherence to the objectives of prohibiting nuclear weapons testing in three media and of non-proliferation of nuclear weapons. Besides, proceeding from the desire to comply with Article III of the Treaty between the Soviet Union and the United States concerning limiting underground nuclear weapons testing, the sides have assumed additional obligations regulating all underground nuclear tests for civilian purposes.

Article II of the Treaty contains the definition of notions concerning underground nuclear explosions for civilian purposes (“explosion”, “shot firing system”, “pattern shot”).

Article III of the treaty confirms that the Soviet Union and the United States having consented to meet their obligations assumed under this Treaty and under other international agreements, retain their right to:

a) conduct peaceful nuclear explosions within their jurisdiction or under their control, beyond the geographical boundaries of the test sites identified in compliance with the terms of the Treaty between the Soviet Union and the United States on limiting underground nuclear weapons tests;

b) conduct, participate and assist in conducting similar explosions in the territory of the nother country on the request of this country.

Concurrently, the sides agreed to prohibit, prevent and not to conduct and assist in conducting anywhere:

- any single explosion in excess of 150 kt;
- any pattern-shots of the total yield exceeding 1.5 megatons;
- any explosions other than for civilian purposes;
- any explosions inconsistent with the terms of the Treaty prohibiting nuclear weapons tests in the atmosphere, in space and underwater, with the nuclear non-proliferation treaty and with other international agreements.

The sides also agreed to additionally consider the issue of conducting separate explosions for civilian purposes in excess of the 150-kt yield.

The control over observance of the Treaty must be accomplished in the following way: first, by employing available national control technologies by the sides in compliance with the generally recognized norms of the international law, second, by exchanging information on scheduled underground nuclear explosions for civilian purposes as well as by providing access to explosion points on certain terms clearly stipulated in the protocol to this Treaty.

The Treaty came into effect on December 11, 1990 simultaneously with the Treaty on limiting underground nuclear weapons tests.

2.5. The Problem of the 1974 Treaty Verification

One of the problems, arisen simultaneously with the Treaty, was the problem of control over its observance. The control over the explosion energy release was assumed to exercise by recording seismic signals, generated by the explosion, by the stations located outside the territory of the country conducting the explosion. The enormous statistics of seismic control results for the Soviet nuclear tests available reveal, on the whole, a good agreement between these estimations and the official experimental results.

Nevertheless, after concluding the Treaty of 1974, time and again the question of enhancing its observance control was raised. No military-technical reasons, substantiating such a necessity, were available. The uncertainty of the seismic control, being in the vicinity of the controlled boundary within the range of 20% deviation from the energy release level, was quite satisfactory for the objectives of the treaty. There was practically no possibility to effectively suppress seismic signals for explosions of such yields. Even a number of nuclear explosions, whose yield would essentially exceed the threshold value of $E = 150$ kt, conducted by one of the sides, could not considerably affect the balance of nuclear forces.

In spite of the completely clear situation, the issue of control lived its own life and eventually, as the curtain of the Soviet nuclear program fell, resulted in 1990 in a new agreement between the Soviet Union and the United States, i.e., the protocol to the Treaty between the Soviet Union and the United States on limiting underground nuclear weapons tests. This fairly cumbersome document signed by the presidents of the Soviet Union and the United States, was remarkable due to its regulation of conditions providing control. The protocol provided for possibility for a controlling side to perform inspections of mine workings and to take its own control measurements for two tests on each test-site annually.

2.6. Development of Nuclear Weapons and Nuclear Testing Under the Treaty of 1974

The intensity of the NTs number and the number of nuclear devices detonated during the tests can serve, as usual, as a common feature characterizing the scale of nuclear programs in force. Table 7.4 presents the annual distribution of these values for the USST and the United States. These values, for the Soviet Union, include the nuclear explosions for civilian purposes (in the United States this program was terminated after 1973), for the United States, they include those conducted in conjunction with the United Kingdom at the Nevada test site.

The data from Table 7.4 cover the period from 1977 till 1990 for the Soviet Union (the last nuclear explosion was conducted on October 24, 1990) and from 1977 till 1992 for the United States (the last nuclear explosion was conducted by the United States on September 23, 1992). On the whole, during the period under consideration, the Soviet Union conducted 259 nuclear tests and nuclear explosions for civilian purposes involving 443 nuclear devices. The United States during that period conducted accordingly 247 nuclear tests involving 267 nuclear devices detonated. These data testify to the fact that a turning point has been reached as the result of implementing nuclear testing programs, i.e. the Soviet Union began outstripping the United States.

Table 7.4

The dynamics of nuclear testing and nuclear explosions for civilian purposes, detonation of nuclear warheads and devices in the Soviet Union and the United States in 1977-1991

	Year	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	Total
USSR	N_{NT}	24	31	31	24	21	19	25	27	10	0	23	16	7	1	0	0	259
	N_{ND}	36	55	52	43	37	34	37	43	19	0	39	29	11	8	0	0	443
U.S.	N_{NT}	20	21	16	17	17	19	19	20	18	15	15	15	12	9	8	6	247
	N_{ND}	23	22	16	17	17	19	20	20	18	15	17	18	16	11	10	8	267

The same relates to the numbers of nuclear tests for domestic weapons-related purposes. Table 7.5 presents the similar data on the intensity of conducting NTs and NEs for the Soviet Union and the United States, disregarding nuclear explosions for civilian purposes and NTs conducted by the United States in conjunction with the United Kingdom.

As consistent with these data, during the period under consideration, the USSR conducted 186 NTs detonating 364 nuclear devices and the United States conducted 230 NTs detonating 250 nuclear devices (NDs). Hence, during that period, the Soviet Union was 1.65-1.45 times ahead of the United States in terms of the detonated NDs (with regard to and ignoring NTs for civilian purposes, respectively). At that, during the period from 1980 through 1984, the USSR was 2.1-1.8 times ahead of the United States in the intensity of conducting NEs (with regard to and ignoring NTs for civilian purposes). The total megatonnage of NTs conducted in the Soviet Union at that time also began to exceed that of the United States (10.9 Mt as against ~ 6 Mt during the period since 1977).

Owing to this, by the time of NT cessation, the USSR was inconsiderably inferior to the United States in terms of the total number of NDs detonated (969 NDs detonated by the USSR and 1151 ones by the United States). In 1980s the quantitative parity in the amounts of nuclear arsenals of the USSR and the United States was attained as well.

Table 7.5

The dynamics of nuclear testing and NDs detonating in the USSR and the United States from 1977 through 1992

	Year	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	Total
USSR	N_{NT}	17	22	22	19	16	11	16	16	8	0	17	14	7	1	0	0	186
	N_{ND}	29	45	39	38	32	26	28	31	17	0	33	27	11	8	0	0	364
U.S.	N_{NT}	20	19	15	14	16	18	18	18	17	14	14	15	11	8	7	6	230
	N_{ND}	23	20	15	14	16	18	19	18	17	14	16	18	15	10	9	8	250

In 1985, the well-developed nuclear testing system actually ceased its existence. M.S.Gorbachev’s moratoria of 1985-1986, 1989-1990 and 1991 destroyed the well-established operational practice. With nuclear explosions conducted in the interim periods between moratoria, their practical role was inconsiderable. These actions promoted the development of environmentalists’ movements around the USSR’s nuclear test sites (primarily, around the major Semipalatinsk test range), which actually joined the fight against conducting nuclear tests in the Soviet Union.

The technology peculiarities of developing nuclear NDs whose yield was in excess of 150kt at the new stage, in the environment of the Treaty in force, were driven by the following tasks:

- upgrading the high-yield NDs earlier developed (primarily in the area of improving the properties of primary modules);
- developing novel higher-yield nuclear devices;
- researching into specific operational features of certain high-yield nuclear devices;
- operational testing of some high-yield devices from ammunition.

With this aim in view, 51 nuclear devices were tested (detonated). 34 ones among them were conducted by VNIIEF and 17- by VNIITF. These numbers do not include individual NTs associated with the direct improvement of primary modules upgraded.

The major efforts involved the development of novel NDs. It was specifically drive by new size-weight requirements for this generation of NDs. To this end, the nuclear tests, 34 in total, were conducted.

It should be mentioned that the operation under small-size explosion conditions led, in a number of cases, to difficulties in interpreting testing results and in estimating the level of full-scale energy release. To solve these problems, essential specialists' efforts, improvement of physical and mathematical modeling of processes, occurring in NDs, and higher-power computing capabilities were needed. In a number of cases, more nuclear tests were to be conducted. The novel NDs developing process became more laborious, longer and more expensive. Such was inevitable Treaty-related cost.

3. Joint Soviet-American Verification Experiments

3.1. Political Background for a Joint Verification Experiment

The improvement of the Soviet-American relations having started since 1980-s, initiated a new phase of the dialogue involving the nuclear tests limitation. In spite of the critical differences remained in the approaches to the control problem, both the sides acknowledged that the complete cessation of nuclear tests was to become the objective of their collaboration in that area.

The full-scale bilateral negotiations on limiting and cessation of nuclear tests became the first phase of the Soviet-American dialogue. They were aimed at developing and agreeing on enhanced measures of control over the observance of the treaty terms of 1974, involving the limitation of nuclear weapons tests and the Treaty of 1976, concerning underground nuclear tests for civilian purposes, which were to bring about the ratification of the said treaties. Hydrodynamic techniques for yield measuring, seismic techniques for yield measuring as well as some types of control-related activities, involving on-site inspections, could be proposed as such enhanced control measures to complete the employment of internal national technologies. The situation involving the "defective" control over the observance of both the non-ratified Treaties persisted for about 15 years.

In 1986, the U.S. president R. Reagan categorically raised a question about enhancing the control over the observance of the threshold Treaty proposing the hydrodynamic technique for yield measuring directly on a testing site as an efficient means for this kind of control. Soon, the Soviet Union and the United States entered upon consultations (1986-1987) on this problem. The consultations resulted in the transition to full-scale negotiations. At that, politicians and diplomats of the Soviet side sought to negotiate a wide range of problems; i.e. limiting and ultimate, stage-by-stage, prohibiting of tests. The American side set a more restrained though a more feasible task, i.e., developing effective control measures for the existing threshold Treaty (1974) and that of 1976 concerning nuclear explosions for civilian purposes.

The performing of even this restricted task involved three-year (1987-1990) intensive efforts of politicians, diplomats, scientists, experimentalists and the military on both sides. As the result, the improved control technologies for underground nuclear explosions, acceptable for each side, were adopted. This found its reflection in signing more protocols to the Treaties. The effort was acknowledged to be a success. Both the treaties were ratified by the parliaments of both the countries in the autumn of 1990. Let us mention right away that the control measures taken were not irreproachable, complete and comprehensive. They were marked with mutual political and technical tradeoffs. Their most blaring weaknesses will be mentioned below.

The United States and the Russian Federation being the USSR's successor proceeded with pursuing new commitments involving enhanced control measures since 1991. At that, due to a unilateral moratorium of the Russian side on nuclear tests, the control over American explosions alone, which terminated in 1992 as well, was exercised.

3.2. Basic Program Provisions Concerning the Joint Verification Experiment

The crucial phase of developing and undertaking enhanced measures of control over underground nuclear tests was the joint experiment involving two nuclear explosions, i.e., one on the test-site of each side (the Nevada and Semipalatinsk test sites). Each nuclear test involves a complex effort including a variety of technologies for ensuring guaranteed underground explosion safety, reliable operation of all automatics components, detonation of nuclear devices, diagnostics and protection, control and recording systems. It is no wonder that with ultimate objectives being very similar, the ways of engineering decisions turned out to be different for each country.

In the experiment, interface means ensuring operational availability of technologies for a controlling party and a host were to be developed in the first place. Account was to be taken of differences in technologies for ensuring safe operation and actuating automatics instructions (field instructions), in the arrangement of operations and communication means. But apart from these technological problems, the joint verification experiment had a major task, i.e., testing of the improved control means proposed to observe the 150-kt threshold, limiting the test yield.

The control means proposed originally included two components, i.e., the hydrodynamic technique for measuring yield (U.S. proposal) – seismic yield measurements by using additional allocated stations in the territory of the country under control (the proposal by the Soviet side).

At that, each of the sides believed that, eventually, the approval of its own proposal alone was quite sufficient. These positions were based on the experience gained by each side and very little known to the other side. The best and the only way to substantiate each of the judgments was a full-scale experiment, in which each of the sides was provided with more favorable conditions to operate, arrange, adjust and debug the equipment, more favorable opportunities to explore than those to be provided directly during the future control.

With the view of verifying the efficiency of the improved control measures comprehensively and impartially, their coordination by the sides and improving the mechanisms for the future control of “threshold” treaties, the Soviet Union and the United States agreed on conducting joint verification experiments. During the Soviet-American summit in Washington on December 9, 1987 the leaders of the departments for foreign affairs of both the countries made a public statement highlighting the agreement in principle on developing control means for the joint verification experiment (JVE).

The major experimental tasks were agreed upon and stated in the Agreement, signed by the heads of the departments for foreign affairs in Moscow on May 31, 1988. They can be summarized as follows:

Each of the sides, on reciprocal basis, can be afforded an opportunity to measure the yield of the JVE, conducted on the test site of the other side, employing teleseismic and hydrodynamics techniques.

Each of the sides also conducts teleseismic measurements for both the explosions of JVEs by using its national network of seismic stations. To ensure these measurements, the sides exchange data on five nuclear explosions conducted from 1978 through 1987, including a date, time, yield, coordinates, depth, geological and geophysical data, teleseismic records of their signals, recorded by five allocated stations, stations corrections and optimal network seismic magnitudes.

Each of the sides conducts hydrodynamic measurements of JVE yield in a special secondary borehole.

The measurement of JVE yield in the primary borehole is adopted to be a reference one, made by using hydrodynamic techniques. Each of the sides reports to the other side on yield values of both the explosions obtained by it by using hydrodynamic measurements in the primary and the secondary boreholes. However, hydrodynamic measuring techniques for the explosion yield in the primary borehole would not be considered by the sides later on as control measures for the Treaty of 1974.

Each of the sides conducts teleseismic measurements of the yields of both the JVEs by employing their 5 seismic stations, the data on which concerning the experiments earlier conducted have been exchanged by the sides. During the JVE the sides exchange the same kind and level of data obtained.

The sides agreed on the identical perception of the JVE’s place and role in the future process of developing coordinated control measures for the Treaty of 1974:

JVE provides the information, by using which each of the sides can demonstrate the efficiency of its hydrodynamic techniques on the test site of the other side. JVE is not directed towards obtaining considerable results in terms of statistics and by no way ensures statistic substantiation for the accuracy of some specific technique for yield measuring. JVEs conducted on both the test-sites provide sufficient information to remove all, apart from statistics, fears of the sides as regards verification techniques proposed by the sides to control the Treaty of 1974 by demonstrating their practical applicability and non-intrusiveness. JVEs will assist the parties in the development to the completion of the procedures for conducting hydrodynamic yield measurements in the secondary borehole and teleseismic yield measurements to control future tests to elaborate the procedure of gathering geological and geophysical data to be exchanged in compliance with any future control techniques.

To better comprehend the essence of the control techniques proposed, let us consider the major peculiarities of setting up underground nuclear tests and the properties of the attendant processes or rather of those critical for the problem under consideration.

3.3. The Hydrodynamic Technique for Yield Measuring

With a nuclear device being detonated, its energy is released in less than a millionth fraction of a second, converting the material of the device, adjacent structures, environment, rocks into highly-heated plasma (with the temperature attaining several kilo-electron-volt). At the initial time, there are regions where the energy density several ten times exceeds that of the sun. This energy is like an uncontrollable compressed spring of non-earthly force rushes outwards driving the development of mighty processes, generating, in terms of their consequence and totality, a phenomenon of a nuclear explosion. At each stage of its development, the nature selects optimal mechanisms for energy transfer.

At the very early moments, with the energy density being so high that its considerable portion is represented by the energy of the thermal electromagnetic radiation, the energy is primarily transferred by the heat-wave-type radiation.

With the wave front moving away from the explosion center, the temperature of the material and radiation behind the wave front drops, thermal processes sharply decelerate and thermal conditions are changed by gas-dynamic ones. The hot plasma, heated by the heat, like an expanding piston, presses the adjacent layers of the dense matter being a moment earlier, for instance, a solid rock. The pressure is so high that it substantially exceeds the strength of atomic bonding in materials and even the elasticity of many external electronic shells of atoms. The material subjected to such pressures is compressed as a totality of ion shells immersed into the electrons medium. At that, it also gets hot but typical temperatures constitute several tens of electron volts and less. Such a material is low-temperature dense plasma whose properties are close to those of non-ideal gas. This plasma gets compressed, under the effect of the pressure applied to it, in much the same way as a gas offering relevant thermodynamic characteristics.

The pulse effect on such a material through application of pressure exerted, in our case, by a hot-plasma piston leads, as in gas, to generating a shock wave. The initial amplitude of this wave alone substantially, by many orders, exceeds all strength and elasticity characteristics of materials. Their characteristic scale is represented by the value $\rho_{\hat{\imath}}c^2$, where $\rho_{\hat{\imath}}$ - is an initial density of the material, c is the effective sound velocity in it. The $\rho_o c^2$ values for rocks constitute units of Mbar. And the initial pressures in the vicinity of the “hot piston” constitute several hundred and even thousand Mbar. So, at this stage of blast development, the primary mechanism of energy transfer is the gas-dynamic one implemented due to a shock wave.

While propagating, the shock wave envelops more and more layers of the material. It conditions the decrease of its amplitude and energy density in it, the reduced velocity of the wave front. At considerable distances from the explosion center $r > r_d = (E/\rho_o c^2)^{1/3}$, when E is the explosion energy, elastic material properties start manifesting themselves, i.e., the variation in the front velocity starts reducing and the velocity value asymptotically tends to the sound velocity in the medium. The linear scale r_d is termed “a dynamic radius of the explosion”. For various rocks, these values constitute 3-5 m/kt$^{1/3}$. At the distances in excess of the dynamic radius, the shock velocity varies inconsiderably.

Actually, in such a real media as rocks, the situation turns out to be more complicated. In many of them, polymorph phase transitions often having non-equilibrium nature, occur. It further complicates the wave’s evolution. On the other hand, in many porous rocks, the skeletons strength turns out to be not very high and the wave’s evolution keeps on effectively conforming to gas-dynamic rules, even at distances essentially exceeding the dynamic radius.

But in any event, for such high-yield explosions, rather a wide region adjacent to the center is available, where the shock motion essentially depends on the energy E released. For instance, if the dependence

$$ct / r_f = F(r_f / r_d) \tag{7.1}$$

is known somehow, where r_f is the position of the wave front at the moment t, then, by measuring these values experimentally and using the above dependence, one can determine the explosion energy.

The most informative for determining the explosion energy is the region of distances less than a dynamic radius. In porous rocks, owing to the additional mechanism of the wave attenuation due to pores’ closing, the non-linear motion region is somewhat greater than that in dense rocks. The region of distances from the center of the explosion, being informative in this respect, is the region of hydrodynamic measurements.

These are the very rules underlying the method for determining underground explosion energy, termed gas-dynamic or hydrodynamic.

3.4. Theoretical and Numerical Basis for the Hydrodynamic Control

The hydrodynamic method is not reduced to obtaining experimental information on shock wave parameters during the explosion. To determine the explosion energy *E*, the knowledge of the dependence of the following view is needed (7.1).

Such dependence can be calculated if:

1. The properties of a specific rock from the test site – the equation of state – are known fairly well over a wide range of thermodynamic parameters.
2. Rather perfect programs are available to calculate the above nuclear explosion processes.
3. Account of specifics of conducting tests is taken with a certain degree of accuracy (the sizes of a testing facility, materials' properties in it, the availability of mine workings and their filling, the existence of hollow channels, etc)

The dependence (7.1) can be obtained experimentally as well. However, in such cases, the following question almost always remains open: what is the effect degree of specifics of the experiment under consideration as against those concrete or averaged conditions taken into account while obtaining a reference dependence. It can cause essential errors when applying the hydrodynamic method.

In any event, to use the hydrodynamic method, additional information, apart from the data on the wave front, for instance, $rf(t)$, is needed, namely:

- on the properties of concrete rocks right from the massif surrounding the nuclear device and located within the measuring area, and materials filling a mine working
- on the conditions of the experimental set up, specifically in the measuring area, including the size and orientation of mine workings, their filling, the existence of voids and channels.

With the generalized experimental approach, the averaged information is used. When calculating (7.1) – type dependences, it is used directly. To enhance the accuracy of the hydrodynamic method, the use of calculated dependences, making the most of the concrete experimental conditions, is preferential.

The rock properties (density, homogeneity, porosity, water-saturation etc.) are explored both directly in situ by using geophysical techniques (neutron, gamma-gamma logging, acoustic probing etc.) and in laboratories (chemical and mineral composition, impact compressibility, behavior under other types of dynamic loading). At that, sophisticated experimental techniques are needed, as a rule, to perform dynamic investigations, which are of special value.

In the area of high temperatures and pressures, being out of reach or not easily accessible for experimental dynamic investigations, use is made of the data on the state-of-the-art theoretical material models. In this event, based on the experimental data on the composition of specific rocks, sophisticated calculations are performed for thermal dynamic material properties needed to describe their behavior. This information along with the experimental data on the impact compressibility, under average (around 1 Mbar and lower) and low pressures, is used to obtain the wide-range equation of state for a specific rock which, in conjunction with the information on other materials, is used in gas- dynamic calculations to obtain the dependence (7.1). The theoretical conceptions are also of importance when dealing with low pressures in the region of polymorphous transformations where there has been no complete understanding, as yet, of the mechanism of dynamic processes.

One more set of data on experimental conditions involves properties of mine workings and of the entire facility where the nuclear device is placed. The information on mine workings can be provided and controlled completely while making arrangements for an experiment. The facility design can provide information on the test objectives and on some parameters of the device under test. Therefore, a part of such information is provided to the controlling side. The incompleteness of this data is one more source of control errors. In particular, with substantial dimensions of nuclear-device-containing containers (the protocol to the Treaty of 1974 allows the application of 3-m-diameter and 12-meter-long containers), possible container-related-effect uncertainties can be so great that they can depreciate the value of the hydrodynamic measurements for the controlling side. For the side conducting the tests and having complete information on the experiments, such a situation can remain acceptable.

The major calculations of shock parameters in the ground for the conditions of the specific test are performed by using highly accurate 1D hydrodynamic calculations. In addition, 2D calculations are performed to take into account distorting factors of mine-workings, diagnostic equipment. The similarity rules of high-yield explosions allow the use of these calculation results as (7.1)-type dependences to obtain the energy of the specific explosion.

For various shock wave front parameters measured, types of dependences (7.1), types of experimental information obtained in tests, data processing techniques, minimizing uncertainties of determining the explosion energy, were developed.

3.5. The Seismic Verification Technique

Beyond the boundaries of the hydrodynamic region, the shock wave intensity still remains so high, though a great deal lower than originally, that it keeps on crushing and splitting up rocks several hundred meters away from the center of the explosion, gradually being attenuated with distance. While traveling upwards, the wave splits off entire slabs. The wave also propagates, decreasing in amplitude, into lower Earth’s strata, penetrates through the crust, enters the mantle. A part of its front passes through the Earth’s core. Several thousand kilometers away from the high-yield explosion, even on the opposite side of the planet, its echo can be recorded as an unusual earthquake by employing special equipment.

Coming across multiple inhomogeneities on its way, such a wave is refracted and reflected. Its energy partially disperses and dissipates in compliance with the rules of those subsurface media whose properties are little known to us. Deep in the earth, in essence, a train of various-type waves is traveling, altogether representing a single blast wave. The intensity of this wave and its components is also related to the explosion energy. Therefore, use is also can be made of seismic waves to determine the explosion energy and the ability to perform measurements outside the test site provides the seismic technique with essential arrangement advantages. Concurrently, the seismic wave bears the information on the explosion center, where the major dissipation of the energy released during the explosion occurs, on the properties of this wave's propagation tract. These peculiarities of the event are have to be taken into account in seismic techniques for determining the explosion energy and, specifically, in the teleseismic technique. The distinctive feature of the latter is the fact that the wave covers an essential part of its way traveling through the Earth's depth strata inconsiderably varying from experiment to experiment for explosions on some specified test site.

By the time of conducting JVE, each of the sides had succeeded in gaining experience of applying the teleseismic technique on its test sites and had experience of observing the explosions of the opposite side. The latter, however, apparently, ensured them no confidence in the reliability of the teleseismic control over the explosion energy, judging by the recurrent differences arising between the sides concerning the adherence to the 150-kt threshold.

The properties of the explosion center considerably differ on various test sites. In particular, the explosion-accommodating rocks are of importance. Are they hard or porous? What is their water supply? What is the stratum geology on the testing site? What are the lower underlayers of the Earth's crust? How deep are they and how does the transition to the mantle occur. All these lead to the fact that the percentage of energy generating a seismic wave can be only within the range of 0.05-3% according to the peculiar features of the explosion center. The variations in explosion centers from explosion to explosion, inevitable uncertainties in the knowledge of them are an essential source of errors of the seismic techniques for measuring the explosion energy. Along with the rich experimental information on the properties of the consolidated rock massifs, on wave processes in them, there are currently reasons to take better account of these properties. At that, both the calculations of wave processes in various explosion centers and the calibration experiments, with the geological conditions and the explosion energy being known, are of major importance. The accumulation of such information on a test site enhances the technique accuracy.

Let us note as well the possible essential effect of certain large-scale technical peculiarities of the testing set-up on the energy of the seismic wave. In particular, when conducting an explosion in large cavities or surrounded with special energy absorbing compounds, additional dissipation of explosion energy is possible, i.e. the decoupling effect leading to its underestimation by using data of teleseismic measurements. Underestimation of energy can be caused, in a number of cases, by the vicinity of chimneys remained from previous tests in the explosion zone.

Therefore, when applying the teleseismic technique as an improved means of control over tests, the obtaining of geophysical information on the center of each specific explosion as well as the technical control over its conditions are needed.
Besides, on pressing demand of the Soviet side, the obtaining of information from 5 recording points located in the territory of the side conducting the experiment was provided for to extend the information obtained in JVEs. Later on, the complex of measures for the enhanced teleseismic control technique, in compliance with the Protocol, included the requirement for taking seismic measurements by the controlling side at three stations of the side conducting tests.

While making arrangements for JVE, the sides exchanged information on five previous explosions using the data of each of the above five recording points. However, the experiment itself was of special importance since the controlling side was for the first time given a chance in it to directly take geophysical and hydrodynamic measurements on the testing site. The calibration for the teleseismic technique was one of the major JVE tasks. In terms of the totality of the above mentioned peculiarities, JVE became a unique calibration event for our teleseismic measurements. Let us emphasize as well that with the hydrodynamic and teleseismic techniques, later applied in parallel, additional favorable conditions were created to improve the accuracy of the latter.

3.6. Some JVE Results

During the negotiations on nuclear tests in Geneva from October 17 till December 14, 1988, the Soviet and American experts headed by V.N.Mikhailov (Soviet Union) and R. Aid (United States) carefully analyzed the results of preparing and conducting JVE.

The discussions led to mutual agreement on many conclusions, recommendations resulting from JVE. Technical experts also came across some areas where there was no complete agreement regarding conclusions and recommendations.

Nevertheless, the sides had a comprehensive exchange of opinions concerning these issues. In particular, again the thoroughgoing debates were started concerning reliability of the hydrodynamic technique as a control measure as applied to conducting tests in large-size containers. These debates never resulted in some positive solution.

The results were to be carefully processed. As to the comparison of the primary experimental information, it confirmed the metrological closeness of the measurements taken by the sides, though, of course, with some discrepancies in details. They were still to be discussed at the future meeting in Geneva. But the most in-depth discussions, apparently, were right on the test sites immediately after the explosions.

The first JVE result was matching the techniques for taking measurements by the sides with regard to exercising hydrodynamic control.

The specialists were provided with an opportunity to familiarize themselves with the geological and geophysical conditions on each test site, to conduct all necessary investigations.

That seemed to us of especial importance due to new unusual environment for each of the sides.

Essentially different was also the technique for taking hydrodynamic measurements. The concurrent measurements allowed direct comparison of the techniques and their capabilities, quality evaluation of the equipment used both in terms of obtaining reliable experimental information and with regard to would-be intrusiveness.

The capability to conduct non-intrusive measurements in principal was demonstrated.

The entire program of teleseismic measurements was implemented in parallel. In terms of our understanding of explosions on the Nevada test site they were fairly efficient. The first test already allowed essential improvements of our techniques for processing seismic data on the American explosions.

Arranging for and conducting of JVEs revealed the drawbacks of our hydrodynamic techniques as a control means (the need for small-size charge-containing containers, the limited range of physical measurements, additional measures related to sensors' geometry correlation, the necessity for taking non-intrusive measures, the need for accurate spatial and time correlation (this requirement contradicts the non-intrusiveness requirement). These drawbacks make it actually impossible to be used for monitoring (for instance, for undeclared explosions).

The teleseismic technique is free from these drawbacks but requires knowledge of geological and geophysical conditions in the region of generating seismic waves

($100\ m/kt^{1/3}$) and the calibration of the seismic track in general. The statistical analysis of the declared explosions shows that the teleseismic technique is able to ensure the measurement accuracy within 30%.

On the explosion yields by using the hydrodynamic measurement results

The yield values of both the JVE explosions obtained by the hydrodynamic measurements are not presented in this paper since the sides have agreed that this information is confidential and can be published with the consent of both the sides.

However, foreign press published the yield estimation of the JVE explosion at the Semipalatinsk test site (STS) using the data of the U.S. and Soviet hydrodynamic measurements constituting 115 kt and 122 kt, respectively.

The discrepancies in yield estimations by the sides based on the results of the hydrodynamic measurements were as follows:

Kearsarge	a primary borehole	8%
	a secondary borehole	14%
Shagan	a primary borehole	7%
	a secondary borehole	0.9%

The results of measuring yields by using the teleseismic technique

The seismic techniques for assessing the yield of underground nuclear explosions (UNE) are based on the rules of the relationship between the explosion yield and the parameters of ground elastic vibrations generated by the explosion. The necessary requirement for justified application of seismic techniques for estimating yield is their calibration, i.e., finding calculation ratios to estimate yield by using the data on standard yields of UNEs and the seismic measuring results for these yields.

The exchange of data on the five earlier nuclear explosions conducted on the Semipalatinsk and the Nevada test sites was accomplished primarily to calibrate seismic techniques for estimating yield and to verify their efficiency.

The exchange of geological and geophysical information in the interests of the teleseismic technique for measuring yield was accomplished in full as stipulated by the Agreement.

Each of the sides had a chance to verify the geological and geophysical information regarding the JVE explosion region adjacent to the primary borehole and extending from the surface down to the depth of nuclear device lying.

The information on geological conditions beneath the depth of device lying and outside the region adjacent to the primary borehole was obtained by extrapolation using the data on core samples from nearby boreholes.

For each of five teleseismic stations, the sides exchanged information concerning their location, rock properties, operation and specifications of seismic equipment.

Each of the sides presented the information on relative procedures for converting measurements taken based on seismic records into the value of the surface displacement.

Each of the sides used its own equations and procedures to determine network-averaged magnitudes for each JVE explosion including station corrections. Network-averaged magnitudes obtained by the sides for ten earlier conducted explosions and for two JVE explosions, agreed fairly well.

Network-averaged magnitudes for earlier conducted explosions and for two JVE explosions and their mean-square errors determined by each of the sides independently on the basis of the “best network” of stations not restricted to ten allocated stations are presented in table 7.6.

The estimated yield value of the Shagan explosion was 125 kt. This yield value was obtained by using the magnitude, taken from the data of national control means, and the empirical dependence of magnitude on the yield, taking into account explosion conditions.

While discussing the determining of the results of the explosion yield, the Soviet side presented the description of application results of the magnitude technique using the exchange results for five explosions earlier conducted at the Semipalatinsk test-site.

It was noted that by using the magnitude value of 6.03 (the U.S. data) and 6.14 (the Soviet data) and the yields of five explosions earlier conducted at the Semipalatinsk test site, one can obtain yield assessments of the Shagan explosion equal to 109 kt and 133 kt, respectively.

Table 7.6

Data on network-averaged magnitudes and their mean-square errors for the earlier conducted explosions and JVE explosions

Country	Testing area	Explosion index	Magnitude	
			Based on Soviet data	Based on U.S. data
U.S.	Yucca-Flat	HE-1	5.97±0.04	5.86±0.02
		HE-2	5.93±0.03	5.90±0.02
		HE-3	5.85±0.04	5.69±0.02

	Pahute-Mesa	**HE-4**	**5.34±0.04**	**5.40±0.03**
		HE-5	**5.59±0.04**	**5.64±0.03**
		Kearsarge	**5.47±0.03**	**5.44±0.03**
USSR	**Balapan N-E**	**HE-7**	**6.14±0.03**	**5.98±0.02**
		HE-10	**6.15±0.03**	**6.01±0.02**
	Balapan S-W	**HE-6**	**6.15±0.03**	**6.13±0.02**
		HE-8	**6.16±0.03**	**6.13±0.02**
		HE-9	**6.06±0.03**	**6.00±0.02**
		Shagan	**6.14±0.02**	**6.03±0.02**

It should be noted that before 1988 no data on yields and conditions of conducting explosions at STS required to calibrate seismic techniques for estimating UNE yield were available to the U.S. side. Therefore, its calculated dependences used to determine UNE yields were plotted by using the substituted data rather than direct calibration and in a number of cases were characterized by substantial systematic errors being the main reason for its protests against the Soviet side's exceeding a 150-kt threshold stipulated by the Treaty of 1974. The situation became essentially different when the data on parameters and conditions of conducting five UNEs at STS were conveyed to the U.S. side on the grounds of making arrangements for JVE and the U.S. side obtained the yield estimation for JVE at STS using the data of its own hydrodynamic measurements and, eventually, due to publishing a paper containing characteristics of 96 UNEs at STS including the data on the yield of 19 UNEs published for the first time.

The data published on UNE parameters at STS allows direct calibration of the magnitude estimation technique for UNE yield by using, for instance, P-and Lg-wave-magnitudes. The P-wave (m_b) magnitude values obtained by using the data of the world's seismic stations network and the Lg-wave (m_{Lg}) magnitude values obtained by using the data of the NORSAR seismic array, considered by foreign seismologists to be the best assessments of seismic UNE energy at STS, were presented in a number of papers.

The parameters of calibration dependences plotted by using the linear regression method, are presented in table 7.7. The calibration dependence for the north-east (NE) region of the Balapan site was plotted for UNEs in the yield (E) region from 16 to 150 kt and for the south-west (S-W) region of the site – from 100 to 150 kt.

Table 7.7

The calibration parameters of the dependences $m_b(m_{Lg}) = a + b \cdot \lg E$ for the Balapan site at STS

Magnitude	Parts of the Balapan testing area	à	b	F
mb	N-E	4.35±0.10	0.77±0.05	1.3
mb	S-W	4.46±0.93	0.77±0.44	1.4
mLg	N-E, S-W	4.26±0.49	0.84±0.23	1.2

F –is the uncertainty factor at the level of confidence 0.95.

When using these dependences, the estimations of JVE explosion yield at STS are as follows:

- *P* - wave-magnitude (m_b = 6.03) – 109 kt;
- *Lg*- wave-magnitude (m_{Lg} = 5.969) – 108 kt.

The yield of Kearsarge explosion estimated by the Soviet experts was 133 kt. Here, the use was made of the spectral – magnitude technique and the data of national technical control means. The application of this technique requiring no knowledge of enclosing rock characteristics in the area of explosion (their variation effects the spectrum of recording signals) was justified in the conditions of null information on geophysical inhomogeneities in the Kearsarge explosion area generated by the explosion earlier (September 30, 1986) conducted.

The joint verification experiment underlay the coordination of control measures which could be used for conformance inspection of the terms of the Treaty on limiting underground testing of nuclear weapons of 1974 and lay the sound foundation for trust in one of the key areas of national security.

Using the JVE results, American and Russian specialists managed to develop and submit for signing the wording of Protocols to the Limited Test Ban Treaty and the Peaceful Nuclear Explosions Treary. In the autumn of 1990 the U.S. Congress and the Supreme Soviet of the USSR ratified both the Treaties and upon exchanging the instruments of ratification in Houston on December 9, 1990 these Treaties came into force.

We believe that signing the protocols would have essentially extended the negotiations if it were not for JVEs, and their putting in to practice would have been much more painful.

The unique joint experiment involving the control over yield of underground nuclear explosions allowed:

- enhancing the confidence level of the two nuclear powers in the nuclear control problem,

- comparison of science and technology levels of ensuring nuclear testing safety,
- developing and practicing applicable improved control technologies thereby accelerating the ratification of the earlier concluded treaties on limiting underground nuclear weapons testing and on peaceful nuclear explosions
- embarking upon a course of scientific collaboration among nuclear-weapons physicists from the two countries in the area of basic and applied researches.

4. On the Comprehensive Nuclear Test Ban

4.1. The Problem of the Comprehensive Nuclear Test Ban

In September 1996, many countries (Russia and the United States included) signed the Comprehensive Test Ban Treaty (CTB Treaty). This treaty had been prepared for a long time and was speeded up in 1993. We are going to consider some reasoning issues associated with this Treaty in terms of ecology and its possible control.

The major environmental damage was caused while conducting first nuclear explosions, i.e., surface explosions accompanied by severe radioactive fall out. The danger was promptly comprehended, the number of and the energy release resulted from such explosions were substantially reduced.

Nuclear explosions in the atmosphere are characterized by shock wave and light effects directly in the explosion area (i.e. within the nuclear test site), the radioactive effect on great masses of the atmosphere (process of meteorological dilution of explosion activity) and in a number of cases by relatively weak activity falling out in the territory. Since the radioactive effect of atmospheric explosions occurred outside the area of nuclear test cites, the general humanitarian problem of cessation of such explosions undoubtedly existed irrespective of various assessments of their would-be effects. The treaty of 1963 on prohibiting nuclear tests in three media ceased conducting such explosions.

Underground nuclear explosions are characterized by two types of environmental effects, namely:

- by short-term effects during the explosion;
- by long-term effects.

The first type involves seismic explosion effects and release of some types of explosion products (first of all, of noble radioactive gases) immediately after the test. The underground nuclear testing safety in terms of these factors is attained due to selecting respective testing conditions and such protection means that outside the nuclear test site there is no environmental seismic effect (it can be recorded only by using special-purpose equipment) and the percentage of radioactive agents does not exceed the peak concentration limit in compliance with the sanitary norms.

In the Soviet Union, the respective technique for under ground nuclear testing, ensuring the compliance with the above conditions, was developed. It was improved due to long-term and persistent efforts and was occasionally accompanied by the enhanced level of the explosion effect. The latter was the result of infringing technology requirements or of the technology deficiencies at the early stages.

The second type of effects relates to underground disposal of nuclear-explosion generated radiation. A nuclear explosion should be mentioned as affording unique opportunities in terms of safe disposal of radioactive materials. First, during the course of a nuclear explosion, radioactive elements are diluted when being mixed in great rock masses (down to the level of $\leq 5{\cdot}10^{-7}$ Ci/g for the time of $T \geq 10$ years following the explosion for nuclei fission products and to the level of $\sim 2{\cdot}10^{-8}$ Ci/g for actinide activity specifying the long-term activity.

Secondly, a nuclear explosion melts ground, which, cooling, transforms into (for silicate-containing rocks) the chemically inert vitreous state, involving the radiation contained in this process. This technique is similar to industrial reprocessing of radiation with its vitrification in special-purpose furnaces for disposal. The nuclear explosion offers a tremendous advantage due the concentration level of vitrified activity in it being of $\sim 10^{-7}$-10^{-8} Ci/g with its level equal to ~ 1 Ci/g in industrial technologies for long-term periods.

Thirdly, the activity disposal occurs very deep in the earth during the course of a nuclear explosion in the separated territory of the test site in the presence of relatively low water flows. On the whole, such activity disposal can be environmentally sounder than natural uranium ore deposits (provided necessary technological measures are taken).

The concern about the planet’s environmental problems, the nuclear testing effect on the habitat included, is quite clear to everyone at the turn of the 20-th century. The experts in the area of nuclear testing were continually concerned about this problem taking enormous efforts to minimize explosion effects and to resolve the problem. Yet, it is of interest to view this question from some other standpoint. It can be asked in the following way: what is the place of environmental safety of nuclear tests among the rest of the ecological problems and to what extent has it been solved as against resolving these other problems?

The major effect of nuclear testing is associated with a certain extent of potential hazards of environmental radiation effects. Another origin of radionuclide production is the word's nuclear power engineering which can be fairly easily compared with.

The production volume of fission products in USSR's underground nuclear testing during the recent years was governed by the energy release level of < 2 Mt/year (corresponds to thirteen nuclear tests each being of 150-kt-yield). The volume of fission products generated by a nuclear power reactor, whose electrical power is P_{el} = 1 GW, is equal to ~ 15 Mt/year. It means that one standard nuclear assembly unit annually produces a factor of ~ 7.5 higher radioactivity of fission products then all USSR's yearly nuclear tests. The power level of the USSR's nuclear power engineering was P_{el} ~ 36 GW, wherefrom it followed that the activity of fission products gene- rated due to nuclear explosions was ~ 0.37% of that produced in the nuclear power reactors (< 2 Mt per year as compared with ~540 Mt/year). On a world's nuclear power engineering scale, the share of this production was still ~ 8.5 times lower and constituted ~ 0.043% (<2 Mt/year as against ~ 4650 Mt/year; P_{el} = 310 GW).

For the actinoid activity, the relative contribution of nuclear tests versus that of the nuclear power engineering was still much lower.

Nuclear tests were conducted in detached territories, i.e. nuclear test sites, deep in the earth, away from densely populated regions. The activity produced at them was buried in the low – concentration chemically inert vitrified state.

The spent nuclear fuel from NPPs (nuclear power plants) is primarily stored in the territories of power plants at specialized on-ground storage facilities. The atomic power plants are located in alive and high-density-population regions. The activity is has been accumulated for decades in enormous amounts and in the concentrated form. For instance, the generation of relatively long-lived fission products from three NPP's units with the power of $Đ_{el}$ = 1 GW each for 10 years is equivalent to the power of 450 Mt-yield nuclear explosions. In a number of countries, the conversion of high-level wastes (HLW) into vitrified state is well developed. However, the share of their productive capacity is relatively low in the total HLW amount and the plants themselves are actually large radiochemical industrial complexes. The problem of establishing long-term environmentally sound storage facilities for reprocessed HLW has not been solved in the least yet.

From all standpoints, the problem of radioactivity produced in nuclear tests seems actually inconspicuous as against the scale of the similar problem of nuclear power engineering. Nevertheless, having been transformed by propaganda means, it was presented as a major world-scale environmental problem.

Let us consider now the problem of capabilities of control over the implementation of the Comprehensive Test Ban Treaty.

First, the technology components of developing NDs without nuclear explosion are unverifiable and, what is more, these types of operation are not related to nuclear tests at all.

Secondly, radiological weapon technologies, where there is no nuclear explosion either, are also uncontrollable and these types of efforts are not nuclear tests either.

Thirdly, detonations of NDs, whose yield exceeds several hundred kg (tons) of the TNT equivalent, are uncontrollable and can be accomplished in special–purpose processing chambers.

Finally, relatively low-yield underground explosions that actually cannot be recorded by the national control equipment can be conducted. Even if the other side has some doubts, concerning this kind of activities in some specific region, special measures can be taken to make the region’s inspection actually ineffective.

In terms of control capabilities, the Comprehensive Test Ban Treaty could not be other than a threshold treaty. Besides, the use of the threshold limit, which could be reliably recorded by national seismic services, seemed reasonable in the first phase. With the control equipment being gradually improved, the threshold level could be reduced. The arrangement of special calibration efforts was apparently reasonable, with each of the sides conducting a set of underground experiments. Thereafter, the sides could exchange actual data on amounts, duration and yield of explosions and on monitoring results obtained by the control equipment. By using calibration results, the threshold value could be accordingly made more exact.

The possibility of conducting peaceful explosions in national and international interests under international control was reasonable to stipulate in the Treaty.

The Treaty on CTB brought about an essential variation in the ND design technique, ensuring its reproducibility and operational capabilities, the need for specialists’ adaptation to new conditions, variation in new ND requirements and properties.

4.2. The Subject of the Comprehensive Test Ban Treaty of 1996

The treaty includes the preamble, 17 articles, two Appendices and the Protocol.

In compliance with Article I of the Treaty

Each member state binds itself to conduct no nuclear weapons tests and other nuclear explosions as well as to prohibit and to prevent any nuclear explosion of this type in any place being under jurisdiction or control

Each member state binds itself to refrain from spurring, encouraging and participating in conduction of any nuclear weapon tests and of any other nuclear explosions.

According to Article II, the CTBT-related organization is to be established to attain the Treaty's objectives and to implement its provisions, the international control observance provision included.

According to Article III, national measures to implement Treaty provisions are to be taken.

Article IV defines the Treaty control conditions, including the international monitoring system, consultations and explanations, on-site inspections, measures to strengthen confidence.

Article VI defines the procedure for dispute settlement.

Article XIV defines the procedure for the Treaty's coming into effect.

The Protocol to the Treaty regulates the Treaty's observance control means.

The Treaty on CTB was opened for signing on September 24, 1996. By now, the Treaty has been signed by 155 countries. 60 countries ratified the Treaty, the Russian Federation included. The Treaty identifies 44 key states whose participation in the Treaty is necessary for its coming into force. Of these states, currently, 41 countries have signed the Treaty and 30 countries have ratified it. The bailee under the Treaty is the UN Secretary General. The CTBT is perpetual.

Table 7.8

Participation of nuclear states in the CTBT

Russia	United States	Great Britain	France	China	India	Pakistan	Israel
24.09.96 30.06.00	24.09.96 -	24.09.96 06.04.98	24.09.96 06.04.98	24.09.96 -	-	-	24.09.96 -

The first date pertains to signing, the second date to the ratification of the treaty.

4.3. Enhancing the Verification of CTBT by Using Regional Small-Aperture Seismic Micro-Arrays Deployed at the Boundaries of Controlled Regions

The major challenge in developing an agreed-on position regarding the Comprehensive Test Ban Treaty is attaining the concord concerning efficiency means for the control over complying with its terms. Developing the proposals for creating the efficient control system has been a major task of the technical assessors having been studying physical and mechanical effects of underground nuclear explosions for a long period. The in-depth examination of this issue by specialists from various countries, holding consultations and scientific workshops at the international level, offers hope that the problem related to arranging the international system of control over conducting nuclear explosions will be solved.

Concurrently, a number of questions concerning the dominating general concept of international control over conducting nuclear tests have arisen. Fort instance, the control system for nuclear testing is projected to ensure reliable recording of physical effects accompanying nuclear explosions irrespective of their location.

In other words, the entire dry-land territory, vast areas of water included, is to be controlled. Since the seismic monitoring remains the major control technique, those complications, emerging on the way of developing a global system for the instrumental control targeted at revealing the events identified as nuclear tests, are natural. The problem discussed showed that the conducting of efficient global control needs a well-equipped network integrating 30-50 special-purpose seismic stations at the least, uniformly deployed throughout the Earth’s surface. Besides, the seismic monitoring is needed to be supported by the radiation one, employing mobile recording stations (presumably, of the on-aircraft type) as well as by the hydro-acoustic monitoring at a number of coastal points.

Yet, even with such a wide network of instrumental monitoring (let us note that its arrangement requires fairly essential efforts and expenditures), the problems persist, associated, first, with an insufficiently low threshold of identifying events which can be treated as nuclear testing (the status of science allows the improvement of nuclear weapons by using the nuclear test results for devices whose yield is lower than 1kt), secondly, with the existence of uncertain control areas.

The reliable recording and identifying of seismic effects of an underground nuclear explosion, low-yield ones (of about 1 kt) included, are known to be possible at regional distances (approximately, up to 1000-2000 km). The international community has not managed to ensure such density for the global control network. The question arises if there is a need for exercising continuous global control over nuclear tests. After all, the technology – based control is merely an auxiliary method to make sure of the fact of nuclear weapon's having been developed. The major technique for the control over the Treaty state-members' nuclear activities is the analysis of technical politics in the area of nuclear and dual-use technologies. It is no secret that even thoroughly kept back facts, concerning the development of nuclear weapons, leak out long before their testing. Therefore, the idea of the nuclear testing control by employing regional seismic stations turns out to be quite practical.

So, let us assume that the international organizations' control of authorized nuclear activities as well as collecting, exchanging and analyzing the information in the area of nuclear materials-and technologies-related acquisition, disposal and intermediary activities will result in revealing a certain CTBT state-member's developing a nuclear device. It is natural to assume that the development will be followed by testing. All this gives occasion to arrange for regional monitoring in the area, accessible to specialists, where a reliable control over would-be nuclear tests is ensured. At this, the arrangement of short-term rather than permanent control points, which, if necessary, can be folded up and transported to another region is possible. Such an approach to control arrangements will, for sure, first, enhance the probability of detecting and identifying underground nuclear explosions due to deploying seismic arrays in the area of reliable recording, secondly, require a great deal lower expenditures for exercising control on the part of the Treaty member-countries.

Actually, no more than 3-5 concurrently operating mobile small-aperture seismic arrays should be available to the community of states having signed the Treaty. At that, the requirements for setting up primary converters and the surveying system infrastructure are substantially reduced (the temporary-operation nature of the seismic array arranged in this way will allow the use of the watch-standing operation principle).

The operation experience available is the evidence of the possibility in principle to deploy a small-aperture seismic array of urgent inspections incorporating one three-component and several one-component recording stations within 3-5 days upon arriving at the location. At that, to re-arrange this array into a regional long-term control station, no longer than 15-20 days are needed.

The Geospheres Dynamics Institute of the Russian Federation has operated a mobile microbus-based complex for the on-line control and diagnostics of local earth's crust areas and regional seismic control. The complex was employed in the following cases:

- at the Semipalatinsk test site when exploring the underground-nuclear-explosion-generated residual seismicity;
- during the seismic monitoring of industrial liquid radioactive waste sites in the vicinity of Krasnoyarsk and Dmitrovgrad;

- during hill side events monitoring in the South Alps region (Grozio city);
- when selecting a building ground for an underground atomic heating plant for the Apatity's heat supply
- for geophysical monitoring of a Moscow's district
- for ranking the earth's crust areas of the Kola region in terms of mechanical stability;
- for industrial chemical explosion monitoring in the open-cast mines of the Kursk magnetic anomaly;
- for diagnostics of the the Mayak plant region.

The complex testing under essentially varying conditions allowed the development of a simple but effective scheme for recording seismic events, collecting and processing data.

When identifying the number of field points for one-component recording and their arrangement throughout the area, the results of in-depth explorations conducted in high-frequency seismic NORESS, GERESS arrays, allowing the operational efficiency comparison between the full seismic-points array and the truncated 4-station array (so-called micro-array) as well as micro-arrays-related own experience.

The equipment for seismic recording stations should meet, as far as possible, the existing requirements for seismic measurements.

The small-aperture micro-array operation was being studied at great length while monitoring hillside events in the South Alps. The scheme of seismic monitoring included two central and two peripheral recording points as well as the center for information collecting, storing and processing, equipped with the digital recording complex EXPRESS.

When controlling, you should surely not restrict yourself to short-time small-aperture well-known NORESS, ARKESS, and others arrays located in the areas requiring control according to the data available.

The essential role of hydro-acoustic monitoring accomplished by employing stationary and mobile (floaters-based) equipment complex is undoubted.

To summarize, it should be mentioned that with such an approach to nuclear weapons control, given all the reduced-cost-related benefits associated with its arrangement and enhanced reliability, one will manage to succeed in addressing other incompletely solved problems regarding the ensuring of the necessary control level should some nuclear-explosion concealment means be applied.

Let us note that here the problems of control over the world's defined area of water are not tackled. It is governed by the fact that the control efficiency is not high: in case of conducting nuclear tests in a far-away ocean's region there by no means can be assured that it will allow the identification of the country responsible for the Treaty violation. In this event, it is essential to rely on data obtained from other (non-technical) control sources.

4.4. The On-Site Inspection Based on Research Results of the Regional Hydrological Conditions and Relaxation Process Conditions in the Rock Massif

The on-site inspection is accomplished by recording relaxation processes occurring in the geological environment. Underground nuclear-explosion-generated residual effect conditions differ from those of natural relaxation processes. The environmental mechanical relaxation involves both explosion aftershocks (distinctly manifested micro-earthquake-type events) and environmental pulse vibrations with amplitudes approaching those of the micro seismic background. The hydro-geological conditions in the explosion area feature pronounced aperiodic nature against the background of natural variations and are associated with reproducing the initial level of underground waters. The complex research into environmental micro-vibrations and dynamics of the underground water level in the earth's crust area under control allows the conclusion concerning the concentrated mechanical effect on the rock massif as well as assessment of its amplitude and coordinates.

The ways of escaping the seismic control, available and improved (decoupling – detonation in the cavity, application of artificial screens, utilizing absorbing properties of deep joint fissures, conducting nuclear explosions against the background of industrial chemical HE explosions), as well as the need for exercising control over underground low-yield explosions require the development of special-purpose inspection techniques for local earth's crust areas where, according to substituted data, a nuclear device was tested.

One of the most promising on-site inspection techniques enabling pin-pointing the territory of the mechanical disturbance of the geophysical environment (to conduct further task-oriented point investigations, for instance, by employing check boring) is the urgent monitoring of explosion-generated-pulse micro-vibrations of geological environment, i.e., of aftershocks as well as of relaxation-type pulse micro-vibrations characterized by a small amplitude and duration as against aftershocks (pronounced micro-earthquake-type phenomena).

The known property of geophysical environment involving a tendency toward getting rid of "excessive" elastic energy accumulated in its separate regions due to an external effect and internal energy release enables the revealing of elevated media relaxation by recording the said pulse seismic phenomena – PSM (henceforth, all pulse media micro-vibrations due to explosions will be called "aftershocks", by tradition).

With considerable similarity of natural and man-made PSMs, explosion-produced seismic events are distinguished by essential time and spatial non-uniformities. These are the very features of relaxation conditions that allow the needed accuracy for indicating the epicenter of an explosion presumably conducted and estimating the scale of mechanical effects (in this case – the explosion energy).

Concurrently, an underground nuclear explosion brings about an essential dynamics variation of underground water. The data available testify to substantial and long-term variations in the underground water level in the region of the explosion conducted.

The interrelation between micro-seismic and hydro-geological conditions of geological environment at the test site seems fairly intriguing and promising in terms of improving the on-site inspection techniques.

4.4.1. On the Mechanism of the Underground Nuclear Explosion's Aftershock Process

The complex block-hierarchic structure of the real geophysical environment underlies a set of its peculiar features, the foremost among which is the accumulation of irreversible phenomena resulted from external disturbances followed by relaxation. In addition, the scale of relaxation processes can be governed not only by the external-effect scale but also by the value of tectonic stress established in the rock massif due to specific area evolution of the earth's crust. The latter, inter alia, means that external disturbances, even weak or moderate in terms of amplitude, can occasionally lead to rather significant consequences entailed by rock shoves, rockslides and micro-earthquakes.

In terms of strain mechanics of solid medium, the underground nuclear explosion-resulted large-scale effects bring about rather considerable irreversible phenomena in the large-volume rock massif. Besides, an underground nuclear explosion can be both an independent source of structural anomalies or non-equilibrium energy fields and a means of spatial redistribution of originally high tectonic stress. Both the events result in generating an area (or a number of isolated areas), whose environmental state is non-equilibrium, in the rock massif. As the consequence, relaxation processes, leading to the medium's tendency to transit to a new (on the whole, different from the initial) equilibrium state, arise (with a certain approximation, the fluctuation of natural stress fields is permissible to be considered as a quasi-equilibrium medium's state as against a strong mechanical effect of the underground nuclear explosion). The said transition is accompanied by emitting seismic waves of varying intensity (explosion’s aftershocks).

The problem of the specific aftershock process mechanism is fairly sophisticated and there has been no definite judgment as yet what the origin of the abnormally high, in terms of relaxation, environment is: tectonic stress specifying the elastic energy store in individual environmental areas or considerable, in terms of amplitude, residual stress resulting from an explosive effect. In the first case, the explosion merely initiates relaxation inducing local energy redistribution in inhomogeneities (a trigger mechanism of explosion-induced seismicity).

In the second case, the explosive effect entirely specifies all the features of the relaxation process without exception. The value of stresses, “removed” as the result of aftershocks, is within 0.3-30 kPa, which, according to estimations, can correspond to both tectonic-and residual-stress values.

Of special interest in terms of environmental energy-exchange processes due to the large-scale concentrated effect and also from the viewpoint of opportunities for inspecting non-identified seismic events, when controlling underground nuclear explosions, is the time structure of the aftershock sequence of various-scale seismic events.

Aftershocks of an underground nuclear explosion are explored by employing highly sensitive local network for seismic recording. For instance, during the underground 35 kt-yield nuclear explosion in borehole 1352 at the Semipalatinsk test-site (July 8, 1989), a small-aperture network for urgent seismic control, involving 5 recording points, was employed. The instrumental seismic monitoring was conducted by 4- to 6 – hour sessions at night. On the whole, 570 varying-amplitude after- shocks were recorded during the measuring period.

The measurement results showed the after-shock emission intensity (the number of after-shocks per unit time N_t) to vary with time t, on the whole, in compliance with the power-dependence $N_t(t) = k \times t^{-a}$ where k and a are the empirical constants. At the same time, the regions, characterized by decreased and increased N_t values versus the averaged dependence $N_t(t)$, are clearly pronounced. The analysis in more detail showed the said peculiarity of the $N_t(t)$ dependence to be related to the atmospheric pressure (P) variation in the region of seismic monitoring. It characterizes high sensitivity of the relaxation process to external effects and, as a result, golden opportunities of the control technique itself.

4.4.2. Spatial Aftershock Distribution

Spatial distribution of aftershocks centers as well as its time variation correlated with spatial characteristics of the underground water flows are also peculiar features of explosion-induced environmental relaxation. Clearly pronounced arraying of PSM centers within the restricted area directly points to the fact that the environment in this area was subjected to abnormally high mechanic effects. Unlike the natural-origin spatial PSM arraying, the arraying area of underground nuclear explosion-induced after-shocks (including that across the depth) features pronounced compactness even in case of non-homogenous environmental structure in the area under consideration. Besides, various-amplitudes aftershock-areas can be considered, with a good approximation, as concentric.

4.4.3. Spatial-Time Characteristics of the Underground Water Level

An underground nuclear explosion leads to essential disturbance of hydrodynamic conditions of underground water. Though the underground level variation is of complicated spatial-time nature specified by specific features of the rock massif, remoteness of the observation hole from the explosion epicenter, the availability of nearby tectonic disturbances, general rules can be identified. For instance, immediately after an explosion in the overwhelming majority of cases, an overall short-term underground flood in observation holes is registered (occasionally, flowing of wells). Thereafter, over a short time period (0.1-3 days) the underground water level is observed to come down to the original one and lower. Most distinctly it is manifested in the explosion near-field zone (at the 0.5-2 km distance) where the recession of level against the initial one can reach 40-m. Later, during a long-term period (from 10 days to 6 months) the stable tendency towards reproducing of the original level is observed.

The hydro-conditions disturbance of underground water was registered to include experimental distances of 10 km for 150 kt-yield explosions. The size and configuration of the explosion-followed underground water drainage area is specified by specific properties of the area and the explosion yield.

The long-term surveillance of the underground water level in the remote observation wells, 5-10 m away from nuclear explosions, testifies to disturbance of natural water conditions over the vast area. At this, the general tendency towards the 2-5 m level recession after the explosion, less pronounced in the boreholes in the vicinity of the feeding area, was registered.

The hydro-geological measurements point to the increased water permeability of rocks, which is directly related to the mechanical state variation of the rock massif resulted from the underground nuclear explosion.

As it follows from the above-stated, the dynamic conditions of underground water in the under-ground nuclear explosion region considerably differs from natural ones and offer pronounced spatial peculiar features.

4.5. Large-Scale Chemical Explosions and the Verification of Underground Nuclear Explosions

The application of seismic control techniques can be essentially restricted by the difficulties associated with the reliable identification of similar-nature seismic events. For instance, possible ways of concealing underground nuclear tests conducted against the background of outstanding industrial chemical explosions or rock shocks are well known. In this case, the problem of identifying seismic events is driven by the capability of differentiating seismic signals generated by various sources. Especially urgent is this problem when the need for identifying small-amplitude seismic events arises. In this case, the seismic signals are comparable in terms of intensity with industrial explosion-induced signals. Given the considerable number of major industrial chemical HE explosions conducted in a variety of countries when extracting minerals and taking construction efforts, the crucial significance of researches, associated with the description of comparative seismic effects of such explosions and determining specific explosion-generated characteristics of seismic signals, should be noted.

The majority of industrial chemical explosions are conducted when extracting solid minerals. At this, especially large explosions are conducted during open mining operations (mineral extracting by open-cast mining). Tens of ferrous and non-ferrous metallurgy enterprises of the coal-mining industry as well as the enterprises, engaged in fabrication of constructional materials and capital construction, conduct hundreds of chemical explosions.

To have an idea of the number of chemical single blasts and their yield, let us turn to table 7.9 presenting some data on the explosions in the Lebedinsk and Stoilensk open cast-mines (Kursk region) in 1994-1995 to illustrate.

It is evident that only in Kursk region several hundred 200-t yield single blasts are conducted annually. Such a situation is likely to occur at the majority of mining enterprises in the would-be participating countries to be involved in signing international agreements on non-proliferation and prohibiting nuclear weapons. For instance, 200-t single chemical blasts are widely used in the United States to fragment ore-bearing rocks involving about 20 mining plants. Each of these plants is involved in tens of such-yield single blasts. So, when exercising control over observing the test ban treaty, an apprehension persists that to conceal an underground nuclear testing, a nation infringing treaty commitments can make use of an industrial high-yield explosion. In conjunction with the decoupling effect (during the blast in an empty cavity) or in case of other techniques used to attenuate an explosive signal this seismic-control-avoiding technique considerably impedes the control over complying with the treaty terms.

Table 7.9

Characteristics of the chemical single blasts in the Lebedinsk and Stoilensk open-cast mines of Russia

HE weight, t	200-400	400-600	600-800	800-1000	> 1000
Lebedinsk MCC, 1992	3	1	6	4	12
Lebedinsk MCC, 1993	11	10	2	4	6
Stoilensk MCC, 1993	10	6	1	-	-

Seismic signals due to underground explosions and industrial high-yield detonation of chemical HE are comparable in terms of magnitude. This is well exhibited by below ratios between *M*-explosion magnitudes and *E*-device yield, obtained for nuclear explosions conducted in the interests of the USSR's natural economy and high-yield detonation of chemical HE.

Statistic data processing yields the following $M(E)$ dependences. For the blasts of conventional explosives:

$$M(E) = 1.33\ \mathrm{Lg}E + 3.96$$

for peaceful nuclear explosions:

$$M(E) = 0.62\ \mathrm{Lg}E + 4.55,$$

where E is the explosion yield in kt

It follows from the above ratios that with the $M(E)$ dependences for chemical and nuclear explosions being qualitatively different, the range of yield is available (0.8-5 kt) where their magnitudes meet. It means that to identify nuclear explosions with the yield equivalent to 100-500 t of TNT conducted concurrently with the industrial chemical explosion of around 1 kt yield, a special analysis is to be performed.

One of the critical problems of nuclear state's cooperative efforts is the development of novel improved and modified equipment and techniques for seismic control over underground nuclear explosions. At that, special attention should be drawn to the problems of identifying and determining underground explosion coordinates by using weak seismic event.