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American and Soviet H-bomb development programmes: historical background

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Contents

Abstract. **The genesis and historical background of the hydrogen bomb are described with particular emphasis placed on the development of physical ideas which led to the discovery of the basic principle of thermonuclear charge construction in the USA and USSR.**

1. Introduction

The invention of nuclear and later thermonuclear weapons has proved to be quite a significant event of the 20th century which has attracted the attention of both scientists and public at large. Those who have been directly involved in the work on nuclear weapons also cannot help taking part in publicising the facts of its evolution. Attention is generally focused on nuclear programmes of the USA and USSR, the nations which were the first to produce the most threatening species of nuclear weapons.

The paper presents a brief survey and analysis of the main events in the history of the creation of the first thermonuclear devices and bombs in the USA and USSR. It spans the period between 1941 and 1956. The sources of information on the history of the American programme used in writing this paper were reports, scientific papers, and books by American authors published in the USA. The main sources of information about the Soviet nuclear programme were original archive documents. An examination of original documents and comparing the course of concurrent events in the USSR, USA, and other countries, one reveals previously unknown connections among them, enlarges the description of the dramatic, albeit unpublicised, competition between the USSR and USA in the development of thermonuclear devices, and yields more reliable answers to many urgent questions concerning the history of thermonuclear weapons in the USSR. These questions are as follows:

— What was the immediate cause for starting the feasibility study of the thermonuclear bomb in the USSR?

— When and under what circumstances did the Soviet government decide to build a thermonuclear bomb?

— How the initially proposed ideas were generated and how were they developed?

— What intelligence information about the USA thermonuclear effort was available in the USSR and when did it arrive?

— How did the intelligence information influence the work of the Soviet H-bomb designers?

— What published information was available to the Soviet team concerning the USA thermonuclear program?

— Why did the approach selected by the Soviet team allow them, in spite of an initial time lag of four years, to reach in 1955 a level, which matched that of the USA (and even to surpass them in some aspect of design and testing of thermonuclear bombs)?

This paper is based on both facts explicitly described in the documents and reconstructions of events (especially in the USA), which follow directly or indirectly from the aggregate of available materials.

This study aims to reveal new details of how the evolution of ideas led to unprecedented technical progress in both USSR and USA, resulting in the construction of highly efficient thermonuclear weapons. It has now become evident that this progress was largely an outgrowth of concepts and information, which were already available on the early stage of the nuclear effort, but, as it may seem, had not been developed and implemented soon enough in either country. This opinion can hardly be endorsed. Scientists in both countries did their utmost to solve in the shortest time a problem that was one of the most formidable challenges in the history of mankind. Given the extraordinarily complex nature of physical processes which occur during a thermonuclear explosion, the early concepts could be developed only after remarkable progress in both mathematical modelling techniques and physical insight into the subtleties behind these phenomena. It took several years of all-out effort in both countries to achieve the required level of R&D. On the

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contrary, looking back from the present, it seems incredible how rapid was the scientific and technical progress in those long-past years unforgettable for the participants of the projects.

2. Brief review and analysis of the main events in the history of the H-bomb programmes of the USA and USSR

The history of thermonuclear research dates back to the year 1941. In May, 1941 Tokutaro Higawara, a physicist at Kyoto University in Japan, suggested in his lecture that a thermonuclear reaction among hydrogen nuclei could be triggered by an explosive chain reaction of uranium-235 fission. In September, 1941 Enrico Fermi presented a similar idea to Edward Teller at Columbia University. The discussions between Fermi and Teller resulted in a concept of using a nuclear explosion to initiate thermonuclear reactions in deuterium. As a result of those discussions with Fermi, Teller was obsessed for a decade by the messianic idea of creating a thermonuclear superbomb.

In the summer of 1942, a team of brilliant scientists from the USA and Europe assembled at Berkely to discuss plans for the Los Alamos Laboratory and mentioned in their talks the problem of a deuterium superbomb. At this meeting Teller outlined initial considerations on which the concept of the 'classical Super' was later to be based. As a result of the wartime effort by the Los Alamos team, the concept of the 'classical Super' was formulated in a fairly consistent version by the end of 1945. It was based on the belief that a flow of neutrons generated in a primary gun-type uranium-235 bomb could ignite a nuclear detonation in a long cylinder filled with liquid deuterium (by means of an intermediate chamber filled with a D–T mixture). The idea of adding tritium to deuterium with a view to lowering the ignition temperature dates back to 1942 and is credited to Emil Konopinski. This concept was based on unpublished (classified at that time) data on the cross section of the D–T reaction. According to those data, the rate of this reaction at relevant temperatures is about one hundred times higher that of the D–D reaction rate in one of its channels. Note that the hopes for the feasibility of the 'classical Super' were pinned to the belief that a nonequilibrium combustion regime in the D–T mixture and pure deuterium could be achieved.

In the spring of 1946, another concept, whose paramount importance became evident afterwards, was suggested during work on the 'classical Super.' Klaus Fuchs, with the participation of John von Neumann, proposed a new triggering device. It included an additional secondary unit with liquid D–T mixture that would be heated, compressed, and, as a result, ignited by radiation from the primary nuclear bomb. A plausible history of the evolution of ideas leading to a radically new concept of radiation compression can be reconstructed from articles and books which were later published in the USA.

During the discussion about feasible designs of more efficient nuclear bombs as early as 1942, Teller proposed an autocatalytic configuration of a nuclear bomb. He proposed placing a boron-10 neutron absorber inside the fissionable material of the bomb. Teller assumed that, as a result of a pressure difference due to ionisation of materials with different numbers of electrons in their atoms, boron-10 would be highly compressed in the process of the nuclear explosion. This compression would lead to a smaller neutron absorption that would result in a higher criticality and energy released by the bomb. Thus, the principle that is sometimes termed as ionisation implosion was discovered.

In 1944 John von Neumann suggested replacing boron-10 in Teller's autocatalytic configuration with a D–T mixture in order to trigger the thermonuclear reaction through heating and ionisation compression caused by the nuclear explosion. Fast neutrons generated by the T–D reaction would increase the number of fissions in the bomb. Von Neumann's idea was a major step on the road to a nuclear bomb with a thermonuclear booster.

In the spring of 1946, Klaus Fuchs, whose preoccupation was how to improve the ignition conditions for the 'classical Super' and who considered utilisation for this purpose of a gun-type nuclear bomb with von Neumann's booster, suggested removing the D–T mixture from inside uranium-235 and placing it inside a beryllium-oxide tamper heated by radiation. He expected that, as in the initial design, the D–T mixture would be heated and compressed by ionisation implosion, so that the conditions would be appropriate for igniting a thermonuclear reaction. In order to contain radiation inside the tamper, Fuchs suggested enclosing the device in a radiation-impervious casing. Since the compression of the D–T mixture in this configuration would be caused by the transfer of radiation from the active zone of the nuclear charge to the zone of thermonuclear fuel outside the nuclear charge zone, this process is radiation implosion. Thus, the principle of radiation implosion was conceived in the spring of 1946.

Fuchs's configuration was the first physical scheme using radiation implosion and a precursor of Teller–Ulam's configuration proposed later. Fuchs's proposal, remarkable for its wealth of novel ideas, was well ahead of its time and could not be developed, given the current state of the mathematical modelling of complex physical processes. It took the USA team five years to fully realise all the benefits that could be derived from Fuchs's concept, which, in turn, involved a development of von Neumann's proposal. It is noteworthy that on May 28, 1946, Fuchs and von Neumann filed a joint patent application for the invention of the new design of the triggering system for the 'classical Super' using radiation implosion.

After Fuchs's departure from Los Alamos on June 15, 1946, the events unfolded as follows.

At the end of August 1946, Teller produced a report proposing a new, alternative to the 'classical Super', configuration of a thermonuclear bomb called the Alarm Clock. The proposed structure consisted of alternating spherical layers of fissionable materials and thermonuclear fuel (deuterium, tritium, and, possibly, their chemical compounds). This design held several potential advantages. Fast neutrons generated in thermonuclear reactions were expected to initiate fissions in neighbouring layers of fissionable materials, which would result in a considerably higher energy yield. The ionisation implosion of the thermonuclear fuel due to the nuclear explosion was expected to lead to its higher density, hence higher rates of thermonuclear reactions. The device could operate without achieving a nonequilibrium regime of thermonuclear combustion, but, on the other hand, demanded a very powerful nuclear trigger to initiate the reactions. The required power of the nuclear trigger was the all higher since the Alarm Clock, as an alternative to the 'classical Super', was proposed for the purpose for obtaining an energy release of the megaton or even multimegaton range in terms of the TNT equivalent. The large dimensions and weight of the structure required in this case made its compression by chemical explosives very difficult, or practically impossible. As of September 1946, theoretical research in the 'classical Super' and Alarm Clock projects continued concurrently at Los Alamos.

In September, 1947, Teller issued a report suggesting using in the Alarm Clock lithium-6 deuteride, a new thermonuclear fuel. With lithium-6 included in the fuel, the quantity of tritium produced during the explosion would be considerably larger, which would notably increase the thermonuclear reaction efficiency. The Alarm Clock project, however, showed little promise at that time. The research in this project slowed down because of almost insurmountable difficulties in triggering the reaction. Nonetheless, theoretical studies of the Alarm Clock continued at Los Alamos concurrently with the 'classical Super' in the following years.

On January 31, 1950, President Harry Truman of the USA launched an appeal directing the Atomic Energy Commission "to continue its work on all forms of atomic weapons, including the so-called hydrogen or superbomb." Truman's public statement gave new impetus to the feasibility study of the H-bomb in the USA. The decision was made to conduct testing explosions of a bomb using thermonuclear reactions in 1951. One of the planned experiments at a test site was an explosion of a 'boosted' nuclear bomb code-named *Item.*

Another planned experiment was the test of a 'classical Super' prototype with a binary triggering device using radiation implosion. This test was code-named *George* and the tested device *Cylinder*. The design of the triggering system in this test was based on the one patented by Fuchs and von Neumann in 1946. It was crucial for the American thermonuclear programme that George test was included in the plan for 1951 and its preparation proceeded. It was the period of preparation to this test when the basic principle of the thermonuclear weapon construction was discovered in the USA. Its main component was confinement of radiation energy released by a primary nuclear charge and its utilisation for compressing and ingiting an isolated secondary core containing thermonuclear fuel.

An important point in the USA thermonuclear programme was that the expediency of conducting the George test had been recognised, and it was not deleted from the 1951 plan, in spite of the negative theoretical results concerning the feasibility of the 'classical Super,' which were obtained in 1950. The prediction of the 'classical Super' failure derived from approximate calculations by S Ulam, C Everett and E Fermi, and was in agreement with von Neumann's calculations performed on the ENIAC digital computer at the end of 1950.

The new principle, however, did not directly derive from the results of work leading to the *George* test. Its discovery was stimulated by a brilliant new idea generated in another field of research. Stanislaw Ulam continued his feasibility study of a two-stage nuclear bomb design, in which a second core with fissionable material was to be compressed by the first explosion and thus initiated, and in January 1951 he proposed a new approach to the thermonuclear bomb problem. He suggested utilising the flow of neutrons generated in the first explosion for compression of a second isolated fusion core filled with thermonuclear fuel by means of specific hydrodynamic lenses. He showed that this configuration would lead to a strong compression of thermonuclear fuel, which would, in turn, trigger a thermonuclear explosion. S Ulam also devised an iterative configuration of a thermonuclear bomb with a chain of similar fusion cores detonating sequentially.

At the end of January 1951, S Ulam presented this idea to Teller, who endorsed the proposal, first with caution, then with enthusiasm, but soon suggested an alternative version, which was, in Ulam's words, "perhaps more convenient and general." Teller suggested deriving energy for the shock compression of the secondary fusion core not from the neutron flow, but from radiation emitted by the primary charge. Teller's configuration of the H-bomb was, in many respects, similar to the design of the trigger in the *George* device. The differences were in that the thermonuclear fuel was not heated by radiation from the primary charge (cold compression yielded higher densities of the thermonuclear fuel), and that a secondary charge of a greater volume and larger mass could be used.

Bearing in mind the similarity between the new ideas and those proposed in 1946 and implemented in the *George* device, Teller declared later that is was a miracle the new concept of the superbomb had not been proposed earlier. The conceptual breakthrough in the H-bomb design, however, could not come before Ulam's ideas.

On March 9, 1951, Ulam and Teller produced their joint report LAMS-1225 "On heterocatalytic detonations 1: hydrodynamic lenses and radiation mirrors." The paper set out the new concept of the thermonuclear weapon design. The new superbomb design, based on a synthesis of Ulam's and Teller's ideas (which, in turn, derived from their earlier concepts and proposals by Fermi, Konopinski, von Neumann, and Fuchs), was named 'Teller–Ulam Configuration.'

On April 4, Teller placed his signature the second LAMS-1230 report, which presented additional calculations related to the feasibility study of a new superbomb performed by Frederic de Hoffmann and suggested a new component, namely a triggering system using a fissionable material placed in the secondary core inside the thermonuclear fuel. Its function was to produce a triggering nuclear explosion inside the compressed thermonuclear materials.

On May 9, 1951, the *George* test was performed successfully. "The largest fission explosion to date succeeded in igniting the first small thermonuclear flame ever to burn on Earth." The test confirmed theoretical predictions about the feasibility of nonequilibrium combustion in the D–T mixture, which was, at least partly, outside the core made from the fissionable material of the primary nuclear charge. The George test, however, had accomplished its main mission prior to its completion, since its explosive device was one of the main precursors of the Teller–Ulam design. The first thermonuclear explosion in the USA was, approximately, their fortieth nuclear test.

In June 1951, Teller and de Hoffmann issued a report devoted to the efficiency of lithium-6 deuteride in a superbomb of the new design. The conference that took place in Princeton on June 16–17, 1951, acknowledged the need for production of lithium-6 deuteride. The USA, however, had no prerequisites for large-scale production of lithium-6 at the time. One of the reasons for this was the discovery that a uranium-235 bomb with a TNT equivalent of several hundred kilotons could be built using an improved chemical implosion technique, and this device could be an alternative to the thermonuclear bomb. The work on such a bomb commenced in the USA in 1950 and ended on November 16, 1952, with the successful King shot. Given the alternative project of a nuclear weapon with a TNT equivalent of several hundred kilotons, it was decided in the USA that only construction of an Alarm Clock with a TNT equivalent well above one megaton made sense, although the feasibility of this project was questionable. Hence, the delay in the construction of a lithium-6 plant. The erection of the USA plant was started only in May, 1952 at Oak Ridge, Tennessee, and it became fully operational in the middle of 1953.

It was decided at Los Alamos in September 1951 to build a thermonuclear device based on the Teller-Ulam configuration for the *Mike* full-scale test scheduled for November 1, 1952. Liquid deuterium was selected as a thermonuclear fuel. The all-out effort in constructing the device, whose design was modified considerably in the process, made it possible to complete the job on time. November 1, 1952, when *Mike* was tested successfully, was a day of glorious achievement for the American thermonuclear programme. The TNT equivalent of the explosion was ten megatons. The device, however, was not a deliverable weapon. The immediate task was construction of a deliverable thermonuclear warhead in the USA. The feasibility of this weapon was, naturally, dependent on accumulation of a sufficient quantity of lithium-6. The minimal required quantity was stockpiled only by the spring of 1954.

On March 1, 1954, the USA performed their first thermonuclear explosion in the new Castle nuclear test series, namely the Bravo shot, which was the most powerful explosion in the history of USA tests. The thermonuclear material in the bomb was lithium deuteride with a lithium-6 content in lithium of 40%. Other tests of this series could afford only lithium deuteride with a low content of lithium-6, including even natural lithium deuteride. All the tests of the Castle series were ground-based, or on a barge in the ocean. Only on May 21, 1956, did the USA drop from an aircraft its first thermonuclear weapon (the Cherokee shot). The aim of that new series of tests performed in May – July 1956 was to achieve progress in designing new, lighter, and more efficient thermonuclear weapon prototypes for various types of warheads.

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Yakov I Frenkel' was the first Soviet physicist who attracted attention in his memo addressed to Igor' V Kurchatov on September, 1945 to "using the high (billions of degrees) temperatures developed in a nuclear bomb explosion in conducting nuclear synthesis reactions (such as production of helium from hydrogen), which are the energy source of stars and could add to the energy released in the explosion of the basic fissionable materials (uranium, bismuth, and lead)."

Although the note gave the erroneous estimate of the temperature generated by a nuclear explosion and the assumption that bismuth and lead were fissionable materials, Frenkel's proposal presented in the note is of interest as the first documented suggestion in the USSR to initiate the release of energy of light nuclei by a nuclear fission explosion. In sending his note to Kurchatov, Frenkel', of course, was unaware that the former had already received information about USA research in this field. First intelligence reports about these developments were delivered to the USSR in 1945. Most of the reports concerning utilisation of light nuclei energy, specifically the superbomb problem, were of a cursory nature. In September 1945, however, the Soviet intelligence service obtained a detailed report describing elements of the theory of the 'classical Super' and characterising features of plausible physical configurations of this device. The basic configuration was described in that report as a combination of a uranium-235 gun-type nuclear bomb with a beryllium oxide tamper, an intermediate chamber containing a D – T mixture, and a cylinder filled with liquid deuterium. The document also characterised the D – T reaction cross sections in the form of an approximate formula and indicated how the ignition temperature of the thermonuclear reaction could be reduced by lightly doping deuterium with tritium. As a result, information about the unique properties of tritium was available in the USSR three and a half years before it was published. Among the intelligence reports concerning the USA activities on the superbomb delivered in the USSR in 1945, there was a report, which deserves special attention, where the superbomb was defined not as a thermonuclear device, but as a nuclear bomb of a higher energy release. The report stated that a first nuclear explosion in that bomb would compress a secondary plutonium-239 sphere and initiate nuclear fission in it. As a result, a higher efficiency and energy release of the bomb were expected. The document, however, gave no clue as to how to implement this concept. Needless to say that an extremely limited circle of people in the Soviet Union were aware of the very existence of these intelligence reports, much less about their contents.

Information about the feasibility of a superbomb was also published in 1945 in the open press. The *London Times* reported on October 19, 1945, the disclosure by Prof. Marcus Olifant, speaking in Birmingham on October 18, that it was then possible to manufacture a bomb about one hundred times more powerful than those dropped on Japan, i.e., with a TNT equivalent of up to two megatons. In his opinion, bombs as powerful as one thousand of existing ones could also be produced in future.

The directors of the Soviet nuclear project could not ignore these reports. On October 24, 1945, the issue of the superbomb was included in the list of questions given to Ya P Terletskiĭ, when he was sent by Lavrentiĭ L P Beria to talk to Niels Bohr on his return to Denmark from the USA. On November 14 and 16 Terletskiĭ had two interviews with Bohr in Copenhagen. When asked whether the reports about a superbomb were true, Bohr responded: "What does it mean, a superbomb? This is either a bomb of a bigger weight than the one that has already been invented, or a bomb which is made of some new substance. Well, the first is possible, but unreasonable, because, I repeat, the destructive power of the bomb is already very great, and the second — I believe — is unreal." Bohr's reply could hardly persuade the Soviet project directors to ignore the reports about the USA studies concerning the superbomb, although it may have reinforced the opinion that both intellectual and material resources of the USSR should be concentrated exclusively on the nuclear-fission bomb effort in that period.

Nonetheless, Kurchatov assigned Yuliĭ B Khariton to consider, in cooperation with I I Gurevich, Ya B Zel'dovich, and I Ya Pomeranchuk, the possibility of using the energy of light nuclei and to report the findings to the Technical Council of the Special Committee chaired by Lavrentiĭ Beria. Their conclusions were summarised in the report "Utilisation of the Nuclear Energy of the Light Elements" delivered by Zel'dovich to the meeting of the Technical Council on December 17, 1945. The suggested approach was based on the assumption of the feasibility of a nuclear detonation in a deuterium-filled cylinder in the regime of nonequilibrium combustion. The report submitted to that session was published in full in *Usp. Fiz. Nauk* **161** (5) in 1991.

After Zel'dovich's report, the Council adopted a resolution with a decision to measure cross sections of reactions between light nuclei, but without any directives concerning theoretical research and computations, or practical work on the superbomb. Nonetheless, in June 1946 a team of theoreticians at the Institute of Chemical Physics of the USSR Academy of Sciences in Moscow, including A S Kompaneets and S P D'yakov and under the direction of Zel'dovich embarked on the theoretical study of the feasibility of releasing nuclear energy from light elements as part of the programme on nuclear combustion and explosion. While Zel'dovich's group conducted their research, new intelligence reports were arriving in the USSR in 1946 – 1947 about the USA superbomb activities. They were supplemented with publications in the open press, including Teller's article in *The Bulletin of the Atomic Scientists* on February 1947, page 35.

On September 28, 1947, Klaus Fuchs, a German-born British physicist, who had just returned to England from the USA, where he had worked on the Manhattan Project, had his first meeting in London with A S Feklisov, a Soviet intelligence officer. Feklisov asked Fuchs ten questions, of which the first concerned the superbomb. According to Feklisov's report about this contact, Fuchs made a verbal statement that theoretical research directed by Teller and Fermi was under way in Chicago. Fuchs described some features of the superbomb structure and principles of its operation, and mentioned the use of tritium alongside deuterium. Fuchs also said that, by the beginning of 1946, Fermi and Teller had proved that the superbomb was feasible. But since Feklisov was not a physicist, he could give only a very approximate description of the superbomb structure and its operation. Whether or not research and design work (R&D) on the construction of a real superbomb were under way in the USA, Fuchs was unaware.

In October 1947 an intelligence report was received in the USSR about attempts undertaken in the USA to initiate a chain reaction in a mixture of deuterium, tritium, and lithium. The report said that there were indications that Teller intended to use such a reaction in a superbomb that would carry his name. It was the first and, very likely, the only intelligence report of that period mentioning lithium as a component of thermonuclear fuel (an important point is that the isotopic composition of lithium was not reported). In earlier reports of 1945 and 1947, lithium, specifically lithium-6, was mentioned only as a starting material for production of tritium in nuclear reactors. It is also possible that the latest report echoed Teller's proposal to use lithium-6 deuteride in the Alarm Clock.

November 3, 1947, was the day when the results of Zel'dovich's group were reported for the first time at a meeting of the Scientific Technological Committee of the First Central Administration at the Council of Ministers. The report by D'yakov, Zel'dovich, and Kompaneets *"Utilisation of Subatomic Energy of the Light Elements"* was presented to the meeting. The authors placed their greatest hopes on nonequilibrium combustion and a possibility of a detonation-like ignition of the reaction by a shock front propagating through the main body of the thermonuclear fuel. They investigated the possibility of detonation in an unbounded medium of deuterium, tritium, and lithium-7 (as they noted in the report, lithium-6 was not taken into consideration because the cross section of the $^6\mathrm{Li} + \mathrm{D}$ reaction was, according to the data available to them, smaller than that of the $^7\mathrm{Li} + \mathrm{D}$ reaction). The problem was solved without taking account of the diffusion of radiation and neutrons. The authors came to the conclusion that a deuterium detonation was possible if the cross sections of secondary reactions were sufficiently large. Detonation in lithium-7 deuteride was thought to be possible if the cross section of the $^7\mathrm{Li} + \mathrm{D}$ reaction were six times as large as the experimental value. The Committee's resolution reiterated the importance of this research for nuclear physics and, if positive results were to be obtained, for practical applications.

On February 8, 1948 the USSR Council of Ministers adopted Resolution No 234-98 "About the working plan of Designing Bureau-11" ("KB-11")†, which, alongside other decisions, directed Zel'dovich officially to KB-11. While working in KB-11, he continued to coordinate work by the group at the Institute of Chemical Physics (Kompaneets and D'yakov) on the problem of nuclear energy from light elements.

March 13, 1948, was marked by an event that played an extraordinary role in the development of the nuclear programme in the USSR and had a considerable impact on the organisation of future activities. On that day Feklisov had a second meeting with Fuchs in London, during which the latter handed over materials that proved to be of paramount importance to the USSR. Among the documents was a new theoretical study concerning the superbomb. It contained a detailed description of the 'classical Super' with a triggering system different from the one designed in 1945. The system had a two-stage configuration and used radiation implosion in its operation. The primary component was a gun-type uranium-235 bomb with a beryllium oxide tamper. The secondary unit contained a D – T mixture with a high content of T. In order to confine radiation within the triggering unit, it was equipped with a heavy jacket impervious to radiation. The primary unit was joined to a long cylinder filled with liquid deuterium. In the upstream section deuterium was doped with tritium. The operation of the triggering system was described. The document included several diagrams characterising the system operation.

The paper contained both theoretical and experimental data relevant to assessing the project's feasibility. The experimental data included measurements of D – T and ^{3} He – D cross sections. The calculations confirmed that the detonation of the D – T mixture in the second stage of the triggering system was possible. The document, however, like the theoretical report dispatched in 1945, lacked calculations that would confirm the possibility of ignition and propagation of the thermonuclear reaction in the main body of the thermonuclear fuel shaped like a cylinder. The ignition of the D – T mixture in the upstream section and the propagation of nuclear combustion through the main body of deuterium were taken for granted, provided that the two-stage trigger operated normally. This information was, probably, consistent with that contained in the Fuchs – von Neumann patent of 1946.

On April 20, 1948 the administration of the USSR Ministry of State Security sent the Russian translation of the

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† The code-name for the Nuclear Centre at Arzamas-16, presently Russian Federal Nuclear Centre — VNIIEF in Sarov. (*Translator's note*.)

materials handed over by Fuchs to J V Stalin, V M Molotov, and L P Beria. The Soviet political leadership interpreted the new intelligence documents on the superbomb and advanced designs of nuclear bombs (which were also given by Fuchs) as a sign that the USA had, possibly, made considerable progress in the development of nuclear weapons, so they called for urgent measures to push through the feasibility studies of similar Soviet nuclear weapons and decided to launch a comprehensive programme officially supported by the central authorities.

On April 23, 1948, Beria ordered Boris L Vannikov, Kurchatov, and Khariton to analyse carefully the materials and submit proposals concerning organisation of studies in connection with the new intelligence. The recommendations in connection with these materials were presented by Khariton, Vannikov, and Kurchatov on May 5, 1948, and formed the basis for the resolutions adopted by the Council of Ministers on June 10, 1948.

Resolution No. 1989-773, adopted on June 10, 1948 ("Supplement to the working plan of KB-11"), prescribed theoretical and experimental feasibility studies of several types of advanced-configuration nuclear bombs and a hydrogen bomb, which was code-named RDS-6 in the document. In the section concerning the H-bomb, KB-11 was commissioned to perform by June 1, 1949, in cooperation with the Physical Institute (FIAN), theoretical studies of thermonuclear ignition and combustion of deuterium and deuterium – tritium mixtures according to the plan specified in the resolution. It also mandated organisation of a special group at KB-11 for studies related to the RDS-6 project.

Resolution No 1989-774, passed on the same day, specified some measures in support of the previous Resolution No 1989-773. In the section concerning the feasibility studies of the H-bomb, the Physical Institute of the USSR Academy of Sciences (directed by Sergeiĭ I Vavilov) was ordered to organise "research in the theory of deuterium combustion in accordance with the specifications from Laboratory No 2† (Khariton and Zel'dovich) and to this end organise at the Institute within 48 hours a special theoretical group under the direction of Igor' E Tamm..." Among its numerous directives, the resolution called for improvement in the living conditions of some participants of the programme, including the provision of a separate living room for Andreiĭ Dmitrievich Sakharov, a member of Tamm's group. On the day, when the two resolutions were adopted, the new intelligence materials were sent by the direct order from Beria to KB-11 so that Khariton could use them in the project. Among theoretical physicists, only Zel'dovich was given access to the latest intelligence. Earlier intelligence documents on the nuclear bombs and the superbomb were available only to Zel'dovich and D A Frank-Kamenetskiĭ among the theorists of KB-11.

In June 1948 the special group of the Physical Institute, which consisted of I E Tamm, Semyon Z Belen'ki, and A D Sakharov, started their research on the deuterium nuclear combustion. Before long V L Ginzburg and Yu A Romanov were also enlisted. The task of Tamm's group was formulated in the resolution so that they had to fulfill it without access to intelligence documents (Kompaneets and D'yakov, being subordinated to Zel'dovich, was also denied access to those reports). The task of Tamm's group was defined as verification and improvement of calculations by Zel'dovich's group at the Institute of Chemical Physics related to the deuterium nuclear detonation.

In analysing calculations by Zel'dovich's group in September and October 1948, Sakharov began thinking about an alternative solution to the problem and considered the feasibility of a combined bomb using deuterium mixed with uranium-238. As a result of this work, he conceived, independently of Teller, the concept of a heterogeneous bomb with alternating layers of deuterium and uranium-238, i.e., a design similar to the Alarm Clock. The design proposed by Sakharov was code-named 'Sloĭka,' which can be approximately translated as 'Layer Cake.' The process of ionisation compression, which was the underlying concept of this design, was dubbed by his colleagues 'sakharization'‡. Note that the article "Superbomb Is Possble" by Watson Davis appeared in *Science News Letter* of July 17, 1948, shortly before Sakharov's proposal. The article presented general considerations concerning the feasibility of the deuterium bomb, and even the section entitled "Combined Bomb", which began with an important remark:

"Because in one of D – D reactions a neutron is produced, it may prove practical to make a sort of combined deuterium – plutonium bomb, using neutrons of the D – D reaction to fission plutonium.

For this reason, any competent chemist could tell you that the material of the superbomb might be a solid consisting of a chemical combination of plutonium and deuterium." Of course, the design of a heterogeneous bomb was not mentioned in the article.

On November 16, 1948, Tamm sent an official letter to Vavilov as director of the Physical Institute to notify him that the research by Tamm's group in the feasibility of the deuterium detonation had led to a conclusion that this material could be detonated differently in a composition of deuterium or heavy water with natural uranium.

On December 2, 1948, Vitaliĭ L Ginzburg produced his second report G-2 on the topic investigated by Tamm's group, "Investigation of the Deuterium Detonation II." Like his first report, this one was dedicated to the feasibility of nuclear detonation in an unbounded liquid deuterium medium. When addressing configurations that could be of practical interest, Ginzburg presented his estimates of the efficiency of the structure including a nuclear bomb surrounded by a layer of deuterium in an outer shell. He remarked that liquid deuterium could be replaced in this structure by heavy water and made another important note: "Another possibility to consider is the 'burning' of mixtures containing lithium-6 (with a view to utilising the heat released in the reaction $\mathrm{Li}^6 + \mathrm{n} \to \mathrm{T} + \mathrm{He}^4 + 4.8$ MeV), uranium-235, plutonium-239 etc." Thus Ginzburg had hit upon the idea of using lithium-6 deuteride as a thermonuclear fuel. It is interesting to observe that the advantage which initially attracted Ginzburg's attention was an increase in the heat release directly related to the neutron capture by lithium-6, rather than the increase in the quantity of tritium produced by the explosion.

On January 20, 1949 Sakharov issued his first report S-2 about the Layer Cake configuration, "Stationary detonation Wave in the Heterogeneous System of Uranium-238 and Heavy Water." This was a comprehensive description of the

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†Presently Russian Research Centre the "Kurchatov Institute."

‡Beside giving the author credit for his invention, this term also created a pun, for in Russian it rather suggests 'caramelization,' because 'sakhar' is the Russian for 'sugar' .(*Translator's note.*)

Layer Cake design and calculations of stationary detonation wave parameters in a Layer Cake unbounded in all dimensions with planar layers. In taking account of secondary reactions with tritium, Sakharov assumed that their cross sections were equal to that of the D + D reaction in one of its channels. He stressed that "the D + T and T + T reactions have not been studied experimentally, and all considerations concerning their cross sections are purely speculative." He also remarked that the investigation of a stationary detonation wave in the 'layer cake' was a prerequisite to solving the problem of igniting the thermonuclear reaction in it. The simplest configuration to be studied theoretically for a start would be that with a nuclear bomb placed at the centre of a large (virtually infinite) spherically symmetrical Layer Cake. At the same time, other configurations, more efficient in terms of the required quantity of plutonium, could be suggested. Among these configurations, Sakharov mentioned "utilisation of an additional plutonium charge for preliminary compression of the Layer Cake." It was, in fact, a concept of a two-stage thermonuclear bomb. Only in five years, in early 1954, Sakharov reconsidered this concept, and in the spring of 1954, when Zel'dovich and he realised the possibility of compressing a thermonuclear device of the Layer Cake type by radiation generated in a primary bomb, Sakharov started intense research with a team of theorists and other experts of KB-11 aimed at implementing the concept in a material structure.

On March 3, 1949, Ginzburg issued the report "Utilisation of ^{6}LiD in the Layer Cake". In considering the efficiency of lithium-6 deuteride utilisation, he had already taken into account generation of tritium due to the neutron capture by lithium-6 and uranium-238 fission triggered by 14-MeV neutrons. It is amazing that, in proposing the utilisation of lithium-6 deuteride, Ginzburg lacked real cross sections of the D + T reaction and, as Sakharov did earlier, he had no alternative but to assume that they were equal to the cross section of the D + D reaction in one of its channels.

After studying calculations by Tamm's group, Khariton forwarded a request to Beria on March 17, 1949, that Tamm and Kompaneets be granted access to intelligence data concerning the cross sections of D – T reactions. After considering this request on Beria's orders, M G Pervukhin and P Ya Meshik responded to their boss that "I E Tamm and A S Kompaneets must be denied access to intelligence materials, for this would enlarge the circle of persons familiar with them beyond necessity." They suggested, however, to hand over to Tamm and Kompaneets measurements of D – T cross sections without a reference to the source. These data were sent to Tamm and Kompaneets on April 27, 1949. Ironically, this event occurred approximately at the time of publication of similar data in *Physical Review* in the issue dated 15 April 1949. It is noteworthy that the General Advisory Committee to the USA Atomic Energy Commission, chaired by J Robert Oppenheimer, recommended as long ago as October 1947 to declassify information on the nuclear properties of tritium.

Given the measurements of the D + T cross section, Ginzburg reconsidered his estimates of the efficiency of ^{6}LiD in the Layer Cake, and presented his new calculations in the report "Detonation wave in the ^{6}LiD system" issued on August 23, 1949. In this report he wrote that the group from the Physical Institute had recently learned about measurements of the D + T reaction cross sections. It turned out that those cross sections were a factor of several tens larger that in the D + D reaction. In this connection, the advantages of the Layer Cake with lithium-6 deuteride became far more impressive and, evidently, only this design was of any practical interest. One can imagine the satisfaction of Ginzburg as a researcher when he found out that his previous results were relevant, despite the lack of required numerical data.

On April 11, 1949, S I Vavilov, as director of the Physical Institute, officially informed Beria about Sakharov's proposal during his work in Tamm's group. On May 8, Khariton sent to Boris L Vannikov his resolution about the Layer Cake. In this document, as in the previous ones, he enthusiastically supported the concept of the Layer Cake and noted that "the underlying idea of the proposal is very ingenious and easily understandable from the physical viewpoint."

In accordance with the decision by the Special Committee of May 23, 1949, several conferences with the participation of Vannikov were organised on June 4 – 9 at Arzamas-16 in order to review the state of the programmes on nuclear bombs and the RDS-6 thermonuclear bomb. On orders from Beria, Sakharov was sent to KB-11 to participate in the conferences and obtain information about the work of KB-11. It was his first visit to Arzamas-16. Information given to Sakharov about the design of the RDS-1 bomb, an analogue of the USA Fat Man bomb, which was under preparation for the first Soviet nuclear test, stimulated Tamm's group to redirect the main thrust of their effort to the spherical layered structure compressed by a chemical explosive.

The plan of research and development of the RDS-6 project for 1949 – 1950 signed by Kurchatov, Zel'dovich, Khariton, Sakharov and others included investigations of both the Layer Cake and the 'Tube' (this was the code-name of the Soviet analogue for the 'classical Super'). Note that the part of the plan concerning the Tube included "triggering of a cylindrical deuterium charge by a gun-bomb explosion or an auxiliary charge containing tritium." This indicates that at the time of the conference Sakharov had some information about the concept and configuration of the classical Super from intelligence reports of 1945 and 1948. By mid-1949, Sakharov's scientific interests in the field of H-bomb, however, were devoted totally to realisation of the Layer Cake concept. The conferences also issued some recommendations concerning organisation of work on RDS-6, but Beria refrained from any administrative decision until President Truman of the USA set out his directive about the continuation of the work on the superbomb on January 31, 1950.

One decision of 1949 concerning RDS-6, however, is worth noting. P M Zernov, director of KB-11, signed it on December 2, 1949 under a command to recruit a team of theoretical physicists into a special RDS-6 group organised at KB-11 by the order of February 8, 1949. Since that time the theoretical department of KB-11 was directly involved in the work on the Tube.

No more than four days after President Truman's directive, the topic of RDS-6 was on the agenda of the meeting of the Special Committee. In accordance with the recommendations by the Special Committee, Resolution of the Council of Ministers No 827-303 "On Measures Ensuring Construction of RDS-6" was adopted on February 26, 1950. The resolution mandated the First Central Administration of the Council of Ministers, Laboratory No 2 of the USSR Academy of Sciences, and KB-11 to organise theoretical, computational, experimental, and design-oriented works aimed at the construction of the RDS-6s (*Sloĭka*, i.e., the Layer Cake) and RDS-6t (*Truba*, the Tube) devices.

Higher priority was attached to RDS-6s, whose TNT equivalent was designed to be one megaton and total weight within 5 tons. The resolution prescribed using tritium not only in RDS-6t, but also in RDS-6s. The target date for the construction of the first RDS-6s device was set to be 1954. Khariton was appointed scientific director of the RDS-6s and RDS-6t projects with Tamm and Zel'dovich as his deputies. The resolution clause related to RDS-6s ordered the completion of an RDS-6s prototype with a small content of tritium by May 1, 1952, and its full-scale test in June 1952 with the aim to verify the correctness of the underlying theoretical and experimental concepts of RDS-6s. The researchers were ordered to submit a draft design of the full-scale RDS-6s device by October, 1952. A group for theoretical research and computations for the RDS-6s project was organised at KB-11 and coordinated by Tamm.

On the same day the Council of Ministers adopted Resolution No 828-304 "Organisation of Tritium Production." Resolutions about the manufacture of lithium-6 deuteride and construction of a dedicated reactor facility for production of tritium followed later.

In March 1950 A D Sakharov and Yu A Romanov arrived at Arzamas-16, in accordance with the Council of Ministers resolution No 827-303, Tamm joined them in April 1950. Under an order from Beria, on March 29, 1950, the intelligence documents of 1948 concerning the hydrogen bomb were sent to the Academy of Sciences in care of S I Vavilov so that I E Tamm and A S Kompaneets could have access to them.

On July 18, 1951 the Scientific and Technical Council of KB-11 considered the state of work on RDS-6s and RDS-6t. Another issue of paramount importance was the construction of a nuclear bomb with a TNT equivalent of several hundred kilotons using an advanced chemical implosion technique. This proposal was made at KB-11 in early 1950. The conference was presented calculations demonstrating that the proposed technique could soon result in the construction of a bomb with a power 50 – 100 times that of RDS-1. Although the amount of fissionable materials needed for this bomb was considerably larger, it seemed fully competitive with RDS-6s. This bomb was later assigned the code-name RDS-7, and its development continued for several years to be completed in the first half of 1953, but, unlike its American counterpart, which was completed with the full-scale test in 1952, RDS-7 was never exploded. The Scientific and Technical Counsel decided at that meeting that the high-power nuclear bomb was a poor substitute for RDS-6s and RDS-6t because the latter two projects, in addition to the highly powerful bombs, solved the problem of how to utilise the nuclear energy of the light elements and to generate, in prospect, virtually unlimited energy. This decision and the above mentioned resolution of February 26, 1950, paved the way for the Layer Cake with a TNT equivalent in the high kiloton range. Later this decision proved to be prophetic since it laid the groundwork for a more efficient two-stage thermonuclear bomb and allowed the Soviet team to gain time in their race against the USA.

By December 17, 1950, Khariton had written a "Brief Report on the Status of RDS-6 devices." He asserted that the work in the Layer Cake was proceeding satisfactorily. Referring to the Tube, he wrote that the problem of ignition conditions of a deuterium – tritium mixture with a high content of tritium confined in a heavy shell around a gun-type bomb had been thoroughly investigated. The result was positive. The mixture should burn out rapidly and generate an intense flow of neutrons, which could trigger (possibly, via an additional detonator, i.e., a volume containing deuterium lightly doped with tritium) the main deuterium charge, if thermonuclear reactions could propagate through this medium.

Khariton's report is a fine illustration of the circumstances, which resulted in such an outcome that the information about the H-bomb design with a triggering system using radiation implosion handed over by Fuchs had not directly led to the invention of a Soviet counterpart of the Teller – Ulam configuration earlier than it was proposed in the USA. One can see that the idea of using an intermediate charge containing a D – T mixture with a high content of tritium had been endorsed by the designers of the Tube. It was assumed, however, that the intermediate D – T charge could be easily heated and compressed, thereby a thermonuclear reaction could be ignited by shock energy. Therefore the basic design selected for this structure contained a gun-type nuclear bomb with a heavy outer shell impervious to radiation. Fuchs's design with a light shell (beryllium – oxide tamper) easily heated by radiation was considered too complicated and was put on the back burner. No computations concerning its feasibility had been performed. The USA researchers, on the contrary, launched intense research of this configuration and based on it the design of the new *Cylinder* device for the *George* test. But the delay in the discovery of the Soviet counterpart of the Teller – Ulam configuration was offset by the development of the Layer Cake.

Although the work on RDS-6s went on smoothly, it became clear in 1951 that the goal of testing the RDS-6s prototype in 1952 was unrealistic. On December 29, 1951, the Council of Ministers adopted Resolution No 5377-2333, which specified measures to ensure the completion of the development and construction, and the test of the RDS-6s prototype in March 1953.

While work on the RDS-6s prototype continued apace, the USA tested on November 1, 1952, the Mike high-yield thermonuclear device. It is interesting to note the reaction of the Soviet leadership to this test. On December 2, 1952, Beria sent a memo to the First Central Administration and Kurchatov, stating: "To I V Kurchatov: The solution to the problem of the construction of RDS-6s is of paramount importance. Judging by some information obtained from the USA, experiment with devices of this type had been conducted. When you and A P Zavenyagin go to KB-11, tell Yu B Khariton, K I Shchelkin, N L Dukhov, I E Tamm, A D Sakharov, Ya B Zel'dovich, E I Zababakhin, and N N Bogolubov that no effort should be spared to successfully complete research and development on RDS-6s. You will also convey this message to L D Landau and A N Tikhonov."

On June 15, 1953, Tamm, Sakharov, and Zel'dovich attached their signatures to the final report on the development of the RDS-6s prototype. The TNT equivalent of the device was estimated to be 300 ± 100 kilotons. It was tested on August 12, 1953. This was the fourth Soviet test in the series started on August 29, 1949. The test of the RDS-6s charge (as the prototype was code-named immediately after its successful test) and was an event of unprecedented significance in the history of the USSR's nuclear programme and a very important step in the construction of Soviet thermonuclear weapons. The measured energy release from the RDS-6s explosion was equivalent to 400 kilotons of TNT and corresponded to the upper limit of the estimated range.

An important point is that the RDS-6s charge was manufactured in the form of a deliverable bomb compatible with the existing means of conveyance, i.e., it was the first prototype of an actual thermonuclear weapon. The RDS-6s design was adapted to large-scale industrial production. But the main result of the work on RDS-6s was the accumulated experience in both science and technology that would guarantee rapid progress in the development of Soviet thermonuclear weapons. Soon this experience was efficiently used in developing a considerably advanced design of a two-stage thermonuclear bomb, and this essentially accelerated its production. But the path to the two-stage thermonuclear charge was a thorny one. Although the idea of the preliminary compression of the Layer Cake by an auxiliary nuclear explosion was proposed by Sakharov as early as 1949, the main difficulty in designing the two-stage bomb was to find a straightforward way to implement this concept. This fundamental difficulty was further exacerbated by one event that had an impact on further progress.

On November 20, 1953, the USSR Council of Ministers adopted Resolution No 2835-1198 "On the Development of a New Type of a High-Yield Hydrogen Bomb." The resolution focused on a version of a single-stage thermonuclear bomb, which was imprudently announced by Sakharov after the successful RDS-6s test. In presenting this project, Sakharov, as he later wrote in his *Memoirs*, pinned his hopes on certain 'exotic' features of the design. It was soon realised that this powerful version of RDS-6s, which was code-named RDS-6sD, showed little promise. But the resolution mandated the team to continue the work, as a result, some theorists were diverted from the mainstream research. Only on June 19, 1955, the Counsel of Ministers decided in Resolution No 1297-734 to postpone the RDS-6sD test (this test never did occur).

It became clear soon that attempts to increase the RDS-6s yield by compressing layers of thermonuclear materials and uranium using chemical explosives were futile, and this led to intensification of the search for the way to implement the two-stage thermonuclear charge. Research in this field was started back in 1952, before the Mike test in the USA. The plan of theoretical sector No 2 (directed by Zel'dovich) for the year 1953, sealed on January 10, 1953, included the clause *"Feasibility Study of Compression of the High-Yield RDS-6s Gadget Using a Conventional RDS (Nuclear Compression)*." The document includes a note that the work was done in cooperation with sector No 1 (coordinated by Tamm).

In 1953 A P Zavenyagin and D A Frank-Kamenetskiĭ suggested an original design of two-stage thermonuclear charges using the material component of energy generated by a primary nuclear explosion. An important event which shifted the focus of all scientists to the two-stage version was the decision to abandon all research on the Tube. This decision was proposed by KB-11 in December 1953 and finalised at the conference in the Ministry of Intermediate Machinery Construction† early in 1954. The decision was based on the aggregate of theoretical results obtained by Zel'dovich's groups at the Institute of Chemical Physics and KB-11, Tamm's group at the Physical Institute, Pomeranchuk's group at the Institute of Theoretical and Experimental Physics, and D I Blokhintsev's group at the Physics and Energy Institute. The decisive contribution to the final stage of research proving the impossibility of nuclear detonation in the Tube was made by groups directed by Zel'dovich and Pomeranchuk.

On January 14, 1954 Zel'dovich and Sakharov sent Khariton a memo "Concerning Utilisation of the Gadget for Implosion of the RDS-6s Supergadget," which described the design and contained estimates of operating parameters of a two-stage thermonuclear charge. The thermonuclear charge, whose diagram was given in the memo, was composed of two units, namely the primary bomb and the secondary thermonuclear unit encased in a massive shell. The memo suggested that the charge should be compressed by pressure produced by gases due to the primary explosion of the primary charge flowing to the zone of the thermonuclear charge. The physical processes during the explosion were described as follows: "The first cycle, i.e., propagation of energy from gadget A (this means the primary bomb) has not been considered. At the beginning of this cycle, more than half of the energy is in the form of radiation, and it is transferred by the radiational heat conductance mechanism. By the end of this cycle, however, a shock is generated with a velocity which exceeds that of the radiation diffusion." Thus the memo lacked in the understanding that it was possible to conduct radiation out of the primary bomb for compression of the thermonuclear unit.

The memo acknowledged that "the utilisation of NC (nuclear compression) was suggested by V A Davidenko." It follows from the available documents and evidence given by those involved in the project that Davidenko's contribution to the 'nuclear compression' concept was primarily in insistently attracting theorists' attention to the two-stage configuration of the nuclear charge (let us recall that the idea of compressing the Layer Cake by a preliminary nuclear explosion was proposed in a general form by Sakharov in 1949). It is also possible that Davidenko contributed to designing the specific configuration described in the memo by Zel'dovich and Sakharov (Zavenyagin and Frank-Kamenetskiĭ suggested designs with different components). Although the configuration proposed in the memo by Zel'dovich and Sakharov was simple, its feasibility was questionable. However tempting the concept of the two-stage thermonuclear charge might be, understanding the great difficulties in its implementation using this and similar approaches drained theorists of any optimism or enthusiasm.

Information about the new powerful explosion conducted by the USA team on March 1, 1954, renewed the drive of Soviet researchers to invent an efficient design of a high-yield thermonuclear bomb. The latest test demonstrated considerable progress in the USA nuclear weapons programme and indicated that it had entered a new phase. It finally became clear that there was an efficient design technique, which had been invented by the American team. The ultimate configuration could be neither the Tube, which had been abandoned by that time, nor the one-stage configuration like RDS-6s. The only configuration left was a two-stage gadget. After a lot of intense thinking and analysis of all the available information and accumulated experience, the Soviet team achieved their goal. A new mechanism for compression of the secondary thermonuclear core by radiation from the primary nuclear charge had been discovered finally. This happened in March and April 1954.

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†A euphemism for nuclear industry. (*Translator's note.*)

The emergence of the new principle was acclaimed by the workers of KB-11 as a sensation. It suddenly became clear how bright the prospects were for constructing new thermonuclear devices. Not only construction of highly efficient thermonuclear charges had become feasible, but also bright horizons for new research in a branch of modern physics of utmost interest, namely the physics of high pressures and high temperatures. The theoretical team of KB-11 had embarked on this research with great enthusiasm. The Branch of Applied Mathematics of the Mathematical Institute, the USSR Academy of Sciences, was charged with the job to confirm the possibility of releasing radiation from the primary unit. The basic configuration in the further investigation was similar to that described earlier by Zel'dovich and Sakharov in their memo, but the alternative mechanism of energy transfer between the primary and secondary units, namely propagation of radiation, was taken into account. In order to confirm the feasibility of the secondary thermonuclear unit compressed by radiation implosion, several intricate problems related to physical processes in interaction between radiation and matter had to be solved. At this point Sakharov made an important contribution by finding auto-modelling solutions to the partial differential equations. These auto-modelling solutions yielded estimates which confirmed the possibility of constructing an efficient device.

The work on the fundamentally new design, which was an counterpart of the Teller – Ulam configuration, proceeded at KB-11 so fast that no documents or scientific papers of priority nature were produced. The only document of the period that could prove the priority in this field of science and technology was the report of theoretical sector No 1 on its activity in the first half of 1954. This report of August 6, 1954, signed by Sakharov and Romanov, contained the following passage in the section *Nuclear Compression*: "Theoretical research of NC is conducted in cooperation with sector No 2. Investigation of the main issues of nuclear compression is under way.

1. Output of radiation from the nuclear bomb for compressing the main body. The calculations have demonstrated that at (deleted) radiation is emitted quite strongly...

2. Conversion of radiation energy to mechanical energy for compressing the main body. It was suggested (deleted). These principles are results of the joint effort by sectors No 2 and No 1 (Ya B Zel'dovich, Yu A Trutnev, A D Sakharov)..."

The all-out effort of 1954 aimed at implementing new concepts in a specific design was analysed at the meeting of the Scientific and Technical Committee of KB-11 on December 24, 1954, chaired by Kurchatov. The committee decided to prepare for an explosion of the experimental thermonuclear charge at a test-site in 1955 with a view to testing the new principle.

By February 3, 1955, technical documents concerning the design of the experimental charge code-named RDS-37 were completed. At that time the crucial theoretical calculations confirming its feasibility were also ready. But calculations and final touches on the RDS-37 design continued right up to its final assembly and delivery to the test-site.

On June 25, 1955, a detailed report on the choice of the configuration and calculations confirming its feasibility was issued. Its authors were E N Avrorin, V A Aleksandrov, Yu N Babaev, G A Goncharov, Ya B Zel'dovich, B N Klimov, G E Klinishov, B N Kozlov, E S Pavlovskiĭ, E M Rabinovich, Yu A Romanov, A D Sakharov, Yu A Trutnev, B P Feodoritov, and M P Shumaev. The title-page also showed the names of all theorists taking part in the project (31 persons). Beside the authors of the report, these were V B Adamskiĭ, B D Bondarenko, Yu S Vakhrameev, G M Gandel'man, G A Dvorovenko, N A Dmitriev, E I Zababakhin, V G Zagrafov, T D Kuznetsova, I A Kurilov, N A Popov, V I Ritus, V N Rodigin, L P Feoktistov, D A Frank-Kamenetskiĭ, and M D Churazov. The report's introduction, written by Zel'dovich and Sakharov, stated that the development of the new principle on which the design of RDS-37 hinged was "an impressive example of creative team work. Some generated ideas (a lot of ideas were needed, and some of them were put forward independently by several authors). Others demonstrated their abilities in designing calculation procedures and analysing contributions from various physical processes. Everyone in the long list of the project participants given on the title page has played a significant role. On the early stage of the work (1952) the participation of V A Davidenko in discussions was very valuable."

The introduction emphasised that the development of the RDS-37 experimental charge could not have been completed without a great deal of design-oriented, experimental, and technological efforts carried out under the direction of Yu B Khariton, the chief designer of KB-11. The report mentioned the names of many participants of the project, and also leaders of mathematical groups, who made invaluable contributions to feasibility studies of RDS-37. The latter were I A Adamskaya, A A Bunatyan, I M Gel'fand, A A Samarskiĭ, K A Semendyaev, and I M Khalatnikov. Mathematical calculations, most of which were performed at the Branch of Applied Mathematics of the Institute of Mathematics, the USSR Academy of Sciences, were coordinated by M V Keldysh and A N Tikhonov.

At the end of June 1955, the theoretical study of the RDS-37 feasibility was reviewed in detail by a commission chaired by I E Tamm and including V L Ginzburg, Ya B Zel'dovich, M V Keldysh, M A Leontovich, A D Sakharov, and I M Khalatnikov. The commission report stated that the new principle opened new avenues in designing thermonuclear weapons. After a detailed consideration of theoretical calculations concerning the feasibility of the RDS-37 design proposed by KB-11, the commission confirmed that it was expedient to perform a test of the device.

On November 6, 1955, a single-stage RDS-27 thermonuclear charge was tested. It was a modification of the RDS-6s device tested on August 12, 1953. The main difference between RDS-6s and RDS-27 was the absence of tritium in the latter, which enhanced the operational parameters of the charge, but, on the other hand, reduced the TNT equivalent within the calculated limits. The charge was fabricated in the form of an air-deliverable bomb and dropped from an aircraft during the test.

November 22, 1955 was the day of a splendid achievement for the Soviet thermonuclear programme. The two-stage RDS-37 thermonuclear charge was successfully tested on that day. It was constructed as an air-deliverable bomb, which was dropped from an aircraft. RDS-37 was distinguished not only for the new technical solutions derived from the new physical principle implemented in its design, but also for its genetic relationship to the RDS-6s design of 1953, specifically the utilisation of lithium-6 deuteride. Tritium was not contained in RDS-37. In order to increase the probability of triggering the charge at the nominal operational parameters, its design had special features. One of the properties of the tested RDS-37 charge was its deliberately diminished power with a view to limiting the risk for local population. The TNT equivalent of the charge was reduced by replacing a fraction of lithium-6 deuteride in the thermonuclear section with a passive material. As a result, the energy of the explosion was approximately half of the initial calculated value. But even in this limited-yield version, RDS-37 was a charge of the megaton range. The measured TNT equivalent of RDS-37 was slightly higher than the expected value, but in good agreement with preliminary calculations (the difference was about 10%). A D Sakharov wrote: "The test was the culmination of many years of labour, a triumph that had paved the road to the development of a wide range of devices with diverse high-performance characteristics (although many challenges would still have to be faced)" The successful test of the first two-stage thermonuclear charge was a milestone, an epochal event in the Soviet nuclear programme.

R&D and tests performed in 1956 marked the beginning of enormous possibilities offered by the new principle of designing nuclear charges. Modifications of RDS-37 with some materials replaced by others, more suitable for large-scale production, had been tested. Measures were taken to additionally reduce the TNT equivalent. The first physical experiment had been performed in 1956, that is, a charge was exploded not for the purpose of testing a new version of a nuclear weapon, but rather of measuring parameters of materials under conditions of a thermonuclear explosion. First experiments had been performed with the aim to design lighter and more efficient versions of nuclear weapons. Many years of hard work lay before the designers of thermonuclear weapons, years that ultimately paid off in spectacular progress in characteristics of thermonuclear charges, as compared to those of 1955 (in addition to the fact that the characteristics of the charges successfully tested in 1955–1956 were considerably upgraded in comparison to those of RDS-6s).

3. Conclusions

1. The final outcome of the race between the USA and USSR in that period was that in 1955 the Soviet programme had achieved the level on par with, and in certain aspects, even ahead of, the USA. These aspects included:

(1) The USSR was the first to use lithium-6 deuteride, a highly efficient thermonuclear fuel, in 1953, in the single-stage thermonuclear charge, and in 1955 in the two-stage device. The USA tested in 1952 a two-stage thermonuclear device with liquid deuterium and in 1954 two-stage thermonuclear charges in which they were compelled to use lithium deuteride with a relatively small content of lithium-6 in Li. Lithium deuteride with a high content of lithium-6 had been used in the USA, probably, since 1956.

(2) Even in the first Soviet thermonuclear tests, agreement between calculated and measured TNT equivalents was fairly good. In 1953 the calculated and experimental explosion energies were in agreement to within about 30%, and in 1955 the discrepancy was about 10%. The calculations and measurements of USA thermonuclear explosions differed by a factor of two or more (the poor accuracy of predictions was, however, partly due to the utilisation of lithium deuteride with a high content of lithium-7, whose nuclear properties had not been adequately studied).

(3) The confidence in the calculations in the feasibility study of the first two-stage charge was so high that Soviet designers intentionally halved the explosion energy in order to limit the risk for the local population.

(4) In the two 1955 tests, the USSR tested air-deliverable thermonuclear bombs. The first thermonuclear test in which the bomb was dropped from an aircraft was conducted in the USA in 1956.

2. In 1945–1946 the Los Alamos team already had at their disposal a wealth of ideas, which later determined the progress in the development of a thermonuclear bomb in the USA and ultimately led to a solution to the very problem of its creation. However, the extreme complexity of the physical processes and the lack of adequate computational facilities at that time delayed for several years the implementation of these ideas and discovery of the basic principle of designing thermonuclear weapons. After acquiring intelligence information about the USA thermonuclear research in 1945–1946 and discovering some key concepts independently (the Layer Cake configuration, the use of lithium-6 deuteride, and, finally, the feasibility of an alternative nuclear bomb free from thermonuclear materials with a TNT equivalent of several hundred kilotons), the USSR had a stock of ideas approximately equal to that of the USA. In implementing these concepts, the Soviet researchers developed concurrently both the 'layer cake' configuration and the fall-back project of a high-yield nuclear bomb (they prophetically anticipated that the Layer Cake would create the prerequisites for constructing thermonuclear bombs of virtually unlimited energy release). The USA team took a more pragmatic course and abandoned the Alarm Clock configuration in the kiloton range, in which it was feasible, but an improved high-yield uranium bomb was quite competitive. They believed that the development of the Alarm Clock, like that of the classical Super, was sensible only in the megaton range, whereas the feasibility of the Alarm Clock in this range was far from certain. This 'gigantomania' in the USA caused a delay in large-scale lithium-6 production, whereas the USSR had everything necessary to build a thermonuclear unit using lithium-6 deuteride by the time the analogue of the Teller–Ulam configuration had been invented.

Theoretical principles for calculations of thermonuclear explosion parameters of such units had been developed in the USSR. It is no coincidence that A D Sakharov in his Memoirs characterised the development of the Soviet two-stage thermonuclear charge as an addition to the 'first' and 'second' ideas (Layer Cake and use of lithium-6 deuteride) of the 'third' idea (compression and initiation of the thermonuclear unit by radiation from the primary nuclear bomb). The Soviet team had made up for the three-year lag behind the USA, which took place at the time when the Teller–Ulam configuration was invented, with a notable margin when the Layer Cake construction was developed and tested. This development led to the Soviet successes in the race against the USA. As a result, a firm foundation was laid for the parity in the sophisticated thermonuclear armaments and subsequent progress in designing more advanced versions of thermonuclear charges.

3. The feasibility study of the use of light elements nuclear energy in the USSR was prompted by intelligence reports concerning work on a superbomb in the USA, the first of which arrived in 1945. The views of Soviet researchers on this subject were discussed at a meeting of the Technical Council of the Special Committee as early as December 17, 1945. However, no decisions concerning organisation of R&D in this field were taken at that time. USSR intelligence reports of

1946 and 1947, alongside publications in the open press, including Teller's disclosure, paved the way for the first resolutions of the Council of Ministers of the USSR on the organisation of research in this field (in particular, recruitment of Tamm's theoretical group) after the arrival of theoretical materials with a description of an H-bomb from Klaus Fuchs in 1948. But the task was formulated as 'verification of the available information' about the feasibility of the superbomb, but not the construction of a superbomb. In the middle of 1949 the first recommendations concerning the organisation of the work on the superbomb in the USSR were outlined, but the highest officials responsible for government decisions on nuclear energy refrained from proposing any resolutions until Truman's statement of January 31, 1950, about his directive to continue the USA programme on thermonuclear weapons. Only after this directive did the USSR's Council of Ministers adopt a resolution on the development of a thermonuclear bomb.

Thus, the USSR's decision to produce a thermonuclear bomb was a reaction to the American challenge. The American president's directive, in turn, was a response to the first Soviet nuclear test.

The highest priority given by the governments to the thermonuclear programmes of both USA and USSR boosted the efforts of American and Soviet researchers in their drive to achieve the goal. Their hard work, rewarded by the spectacular achievements of 1952 – 1956, however, was not limited to the construction of the first deliverable thermonuclear charges. The new Teller – Ulam concept of design and its Soviet analogue unleashed enormous potential for further improvements of nuclear weapons and transformed the competition between the USA and USSR nuclear researchers into a virtually unlimited nuclear arms race.

The decades of the nuclear arms race are over at long last, and the process of nuclear arms reduction has begun, but the negative consequences of nuclear stockpiling have yet to be overcome. Nonetheless, the possession of nuclear weapons by both superpowers had, undoubtedly, prevented war between them. During the historical period in the wake of the cold war, the nuclear arms remaining in the possession of the major powers after radical reductions should guarantee global stability and security all over the world.

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