the initial ideas and proposals in the field of research and the creation of industrial-scale power installations in the USSR; these installations were mostly based on the controlled fusion reactions of heavy hydrogen isotopes (deuterium and tritium); the article also analyzes a number of events connected with the history of the invention of the hydrogen bomb.

The highly complimentary reviews of A D Sakharov and I N Golovin in respect of Lavrent'ev's work of 1950 state unambiguously his priority in formulating the need for creating industrial-scale power plants based on CNF in the USSR. The archive materials only went to confirm the words of O A Lavrent'ev, A D Sakharov, Ya B Zel'dovich and I N Golovin.

As for the principal designs of hydrogen bombs as given by O A Lavrent'ev in his preprint [8], I need to say that they appear to be quite reasonable for the initial analysis and contain certain physical ideas and potentials. However, their degree of novelty and significance in that period (the 1950s) can only be evaluated by a specific and detailed analysis of the original documents.

As for the proposals to use a solid chemical compound, lithium-6 deuteride, as a thermonuclear fuel in the hydrogen bomb, the priority here definitely belongs to V L Ginzburg (end of 1948 — beginning of 1949). O A Lavrent'ev came up with this proposal 18 months later (but independently), while the American side came to this phase, as far as we can judge from publications, by mid-1951, and carried out the first test explosion of a hydrogen bomb charged with lithium-6 deuteride ('Bravo' test explosion) on March 1, 1954.

We can conclude, therefore, that the available archive and open publication material supports the statement that the role played by O A Lavrent'ev in initiating the nuclear fusion research in the USSR is fully deserving of being included in the historical presentation of the subject.

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The 50th anniversary of the beginning of research in the USSR on the potential creation of a nuclear fusion reactor

G A Goncharov

1. Introduction

Fifty years ago, on May 5, 1951, I V Stalin approved USSR Council of Ministers Resolution No. 1463-732ts/sd "On conducting research and experimental work to clarify the feasibility of building a magnetic thermonuclear reactor" (abbr. ts/sd stands for Top Secret/Special dossier). A month before that, on April 5, 1951, he approved the USSR Council of Ministers Order No 4597-rs on starting the work of designing the MTR-L facility — a laboratory pilot model of such a reactor. These documents were not only the first in the

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USSR but also the first governmental acts in the world that ordered and regulated the necessary work, assigned responsibilities and outlined the measures supporting the effort.

The Resolution of May 5, 1951 began with the following words: "*Recognizing the importance of the proposal made by Cde. Sakharov A D to use the intranuclear energy of light elements with the aid of a magnetic thermonuclear reactor* (*facility 'MTR'*), *USSR Council of Ministers ORDERS:*

1. To bind the First Main Directorate [1] (Cdes. Vannikov [2], *Zavenyagin* [3], *Kurchatov*) *to organize research, design and construction work on the clarification of the feasibility of generating a self-sustained thermonuclear reaction using a magnetic thermonuclear reactor; they will support and guarantee the fulfillment of the following tasks*:..."

The work encompassed in the Resolution included the development of the theory of the magnetic thermonuclear reactor and the construction, in addition to a small-scale MTR-L reactor, a large laboratory MTR-L2 model aimed at generating neutron radiation. The main research program intended to clarify the feasibility of creating a thermonuclear reactor was concentrated at LIPAN (Laboratory of Measuring Instruments of the USSR Academy of Sciences, currently the Russian Research Centre 'Kurchatov Institute'). The scientific leadership of the program on the feasibility of MTR lay on the shoulders of L A Artsimovich, his deputy on the theoretical side being A D Sakharov, and on the design and construction, D V Efremov. M A Leontovich was chosen to head the theoretical part of the work on MTR at LIPAN.

The Resolution ordered the First Main Directorate and the institutions involved in the program to present by October 1, 1952 their conclusions on the feasibility of designing and constructing an MTR facility on an industrial scale, outlining the main parameters of the facility.

To discuss the aspects involved in developing the MTR project, a scientific and technical commission was formed in LIPAN. It was chaired by I V Kurchatov and included L A Artsimovich, I N Golovin (the two deputies of the chairman), A D Sakharov, I E Tamm, M A Leontovich, V V Vladimirskiĭ and D V Efremov (the text of the Resolution is copied in the Section "From the Archive of the President, Russian Federation", p. 859 in this issue of *Physics-Uspekhi*).

2. A D Sakharov's first reflections on how to create a controlled thermonuclear reactor

It is certainly most interesting to look into the history of events and the emergence of ideas that led to the first government-level decisions to start work on the exciting problem of creating a controlled thermonuclear reactor.

In his *Memoirs*, A D Sakharov noted that he first thought about controlled fusion reaction while going in a train to visit Yu B Khariton's 'object' [4] for the first time in June 1949: "*That night in my stuffy compartment, I couldn't sleep. It was not that I was mulling over distressing events or my own mistakes, as is often the case now when I suffer from insomnia; what kept me awake was a new and challenging idea, the possibility of a controlled thermonuclear reaction. But it would take me another year to find the key to a promising approach to magnetic thermal insulation* (*Tamm backed this idea and played a role in its development*)" [2, p. 155].

This trip was organized on L P Beriya's personal instructions [5] because of a number of meetings that were organized at KB-11 between June 4 and 9, 1949; the meetings discussed the state of affairs on preparing a test of the first Soviet atomic bomb (RDS-1) and on the results achieved in the program adopted by the USSR Council of Ministers (Resolutions No. 1989-773ts/sd and No. 1990-774ts/sd approved on June 10, 1948). The first of these resolutions ordered the theoretical and experimental verification of data concerning the creation of improved atomic bombs (compared to the implosive RDS-1 and the gun type RDS-2 being developed at the time) and also the hydrogen bomb; the second resolution listed the measures that supported the implementation of the first [1, pp. 494 – 498], [3, p. 1099], [4, pp. 52, 53]. One of these measures was the installation at the USSR Academy of Sciences Physics Institute of a special team led by I E Tamm and consisting of S Z Belen'kiĭ and A D Sakharov, later joined by V L Ginzburg and Yu A Romanov. As I E Tamm formulated it, the team's task was to conduct the theoretical and computational work clarifying the feasibility of developing the hydrogen bomb, more specifically to verify and improve calculations that were carried out at the time at Ya B Zel'dovich's group in the USSR Academy of Sciences Institute of Chemical Physics (this group was doing model computations on the deuterium 'pipe' problem, which is an analogue of the American 'classic super' [6]. Having first started with analyzing the reports of Ya B Zel'dovich's group, A D Sakharov "*radically changed the direction of our research*" in autumn 1948 by proposing an alternative design for a thermonuclear charge "*that totally differed from that pursued by Yakov Zel'dovich's group in both the physical processes accompanying explosion and even the basic source of the energy released*" [2]. A D Sakharov's proposal was soon essentially complemented by V L Ginzburg [2, p. 149]. A D Sakharov's suggestion was a 'layer cake' design: a fusion charge comprising alternating layers of uranium and thermonuclear fuel — heavy water (Ya B Zel'dovich's group analyzed the fusion charge with liquid deuterium). V L Ginzburg's proposal was to employ the more efficient lithium-6 deuteride as the thermonuclear fuel in the layer cake [3, 4]. Ginzburg formulated, justified and developed his proposal between December 1948 and August 1949. A D Sakharov completed his first report on the 'layer cake' in January 1949. In April 1949, S I Vavilov, director of the P N Lebedev Physics Institute (FIAN), officially informed L P Beriya about A D Sakharov's proposal. At the end of May 1949, L P Beriya decided to send A D Sakharov to KB-11 to get acquainted with the work at this site and to take part in the generation of the draft plan for further work on the hydrogen bomb. The outcome of this decision was that A D Sakharov, the only one out of I E Tamm's team, went to KB-11 in June 1949.

[1] The First Main Directorate of the USSR Council of Ministers is a government body for directly administering the research, design and construction organizations as well as industrial plants in the uses of atomic energy and the manufacturing of atomic bombs. It was created by the State Defense Committee Resolution on August 20, 1945 [1, pp. 11 – 14].

[2] B L Vannikov was the head of the First Main Directorate.

[3] A P Zavenyagin was at the time the first deputy of the head of the First Main Directorate.

[4] It was then called the Design Bureau No. 11 (KB-11) of USSR Academy of Sciences Laboratory No. 2. At the moment it is the Russian Federal Nuclear Center 'All-Russia Research Institute of Experimental Physics'.

[5] L P Beriya headed the Special Committee of the USSR Council of Ministers, which was a government body founded by the USSR State Defense Committee's Resolution on August 20, 1945 to lead and coordinate all work on the uses of atomic energy.

[6] See Refs [3, 4] and Section 6 of this paper.

Note that *Science News Letter* of July 17, 1948 published a paper "Superbomb is possible" by Watson Davis [5]. Davis concluded that it was certainly within the possibility of designers to develop an atomic superbomb a thousand of times more powerful than existing plutonium bombs. The bomb would mostly consist of deuterium. The article, however, had a special section called "Combined bomb". It carried a remark that because in one of the two D + D reactions a neutron is produced, it may prove practical to make a sort of combined deuterium – plutonium bomb, using the neutrons of the D + D reactions 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*" [5]. It cannot be excluded that A D Sakharov's proposal of a 'layer cake' was stimulated by W Davis' article. A 'layer cake' proposed by Sakharov was just the combined bomb, you see. However, A D Sakharov suggested to use instead of a compound of deuterium with plutonium, i.e. instead of a homogeneous mixture of deuterium with the heavy fissile material, a more efficient combination of thermonuclear fuel and fissile material — a heterogeneous layered design. What happens in this system in the course of the explosion is the ionization-driven compression of the thermonuclear fuel, which increases the intensity of thermonuclear combustion and therefore the intensity of uranium fission by fusion-produced neutrons (A D Sakharov's colleagues in jest referred to the process of ionization-induced compression in the 'layer cake' as 'sakharization').

It is also possible that Watson Davis' article prompted A D Sakharov to think of a controlled thermonuclear reaction. This article ended with the following exceptional predictions: "*Even if more powerful bombs are not needed, research should continue on nuclear energy from deuterium. Power plants of the future might be run on this atomic fuel. The production of a continuing* (*chain*) *reaction that won't explode should be as possible with heavy hydrogen as with uranium. And there is probably more heavy hydrogen than uranium on earth*".

3. O A Lavrent'ev suggests a project for a thermonuclear reactor with an electrostatic field. A D Sakharov comes up with an idea for magnetic thermal insulation of the plasma

Let us look now at the situation in which A D Sakharov hit on the idea of plasma magnetic thermal insulation — a promising approach to solving the problem of controlled thermonuclear synthesis. "*Although these questions were already on my mind in 1949, as yet I had no concrete intelligent ideas. Then, in the summer of 1950, Beriya's Secretariat sent us a letter from Oleg Lavrent'ev, a young sailor in the Pacific Fleet*[7]*, who noted* (*in the introductory part*) *the importance a controlled thermonuclear* (*i.e. fusion*) *reaction might hold for future power engineering and then offered a proposal to create a high-temperature deuterium plasma by means of a system based on electrostatic thermal insulation. Specifically, he proposed that two or three metal grids be used to surround the reactor volume. A potential difference of several dozen keV, applied to the grids, would create an electrostatic field that would retard the escape of deuterium ions or* (*in the case of three grids*) *the escape of ions from one of the gaps, and electrons from the other. I wrote back that the author's idea concerning controlled thermonuclear reaction is of great importance and that Lavrent'ev had raised an issue of immense significance. This testifies that he had displayed initiative and creativity that merited all possible support and aid. His specific plan, however, struck me as impracticable: there was no way to ensure that the hot plasma would not come into contact with the grids, which would inevitably result in enormous heat release and render such means incapable of attaining sufficiently high temperatures for thermonuclear reactions to run. I probably should have mentioned that Lavrent'ev's idea might prove fruitful in conjunction with other ideas, but at that time I had nothing specific to suggest and I did not write the appropriate phrase. My first vague thoughts on magnetic rather than electrostatic thermal insulation occurred to me as I read Lavrent'ev's letter and wrote my referee comments. ...*" [2, pp. 197, 198].

A D Sakharov emphasized the principal difference between magnetic and electric fields: magnetic lines of force close on themselves (so that closed magnetic surfaces can be formed), which could make the application of a magnetic field an efficient way of solving the problem of avoiding the contact of the hot plasma with the walls. "*The appearance of closed magnetic lines of force is particularly evident within the interior of the toroid, when the current passes through the toroidal winding situated on its surface... It was this sort of system that I decided to explore. Igor' Evgen'evich* (*Tamm*) *returned to the installation from Moscow at the beginning of August 1950... He responded enthusiastically to my ideas, and from that time on the development of the notion of magnetic thermal insulation was entirely the product of a joint effort... Initially, I had suggested that our project be called TTR* (*toroidal thermonuclear reactor*)*, but Tamm came up with the happier designation MTR* (*magnetic thermonuclear reactor*)*; this more general name stuck, and is now applied to other systems using magnetic thermal insulation as well*" [2, pp. 197, 198].

The first difficulty that A D Sakharov and I E Tamm immediately faced was the problem of drift of charged particles owing to the nonuniformity of the magnetic field and also owing to the electric field that would send some particles into the walls of the toroidal volume. A D Sakharov and I E Tamm thought of overcoming the difficulty by "*considering systems in which a field created by the circular current flowing inside the toroidal space is superimposed on the field set up by the toroidal winding*" [2, p. 199]. A D Sakharov wrote: "*In our first proposals we considered two possible ways to set up the circular current — with the aid of a special current-carrying ring placed inside the reactor space or an induction current flowing directly through the plasma and created by pulsed currents in secondary circular windings situated outside the toroidal space... We submitted our proposal in writing and did something that was even more important at the time — we told Igor' Vasil'evich Kurchatov of our ideas*" [2, p. 200].

[7] When O A Lavrent'ev formulated his proposal, he was a senior telegraph operator on conscription duty in 1946 – 1950 in a military unit stationed on Sakhalin Island; his rank was junior sergeant. O A Lavrent'ev's suggestion was sent to Moscow on July 29, 1950 and addressed to the Head of the Department of Heavy Engineering Industry of the Central Committee of the Communist Party of the Soviet Union (CPSU), I D Serbin. It was entered into the books of the CPSU secretariat and moved to the Special Committee and then transferred to KB-11, via the First Main Directorate, where it was reviewed by A D Sakharov. Sakharov's referee report on O A Lavrent'ev's proposal is dated August 18, 1950.

4. Preparation and acceptance of the first governmental decisions on the research into the feasibility of creating a thermonuclear reactor

The sequence of events that led to the first governmental decisions on the work related to the problem of a controlled thermonuclear reactor was as follows.

In **October 1950,** A D Sakharov and I E Tamm reported the principal design of the suggested magnetic thermonuclear reactor to the first deputy of the First Main Directory, N I Pavlov [6, L. 8].

On **January 11, 1951,** I V Kurchatov, I N Golovin and A D Sakharov sent a letter to L P Beriya in which they wrote:

"*Taking into account that magnetic nuclear reactors may become very important for nuclear-based power engineering, we consider it necessary to construct a laboratory model at LIPAN in 1951 and study with this model the fundamental physical properties that determine the feasibility of creating industrial-scale reactors... We intend to gather a team of experimenters and theoreticians among the staff of LIPAN; however, the work will require working contacts with the authors of the model of the reactor, Cdes. Sakharov A D and Tamm I E and also Cde. Ginzburg V L from FIAN, who has carried out important theoretical studies on the magnetic thermonuclear reactor. We request Your permission to prepare a draft Resolution of the USSR Council of Ministers on measures supporting the construction of a magnetic nuclear reactor model and to submit it to You for evaluation*" [6, Ll. 3 – 11].

Already on **January 14, 1951,** L P Beriya sent a letter to B L Vannikov, A P Zavenyagin and I V Kurchatov which began with the following words [6, L. 12]:

"*In my opinion, the work on the creation of a new type of reactor that is being carried out at KB-11 on the initiative of Cdes. Tamm and Sakharov is extremely important and therefore everything needed for its successful progress must be implemented and, first of all, it is necessary to do everything required to verify as soon as possible the theoretical and technical feasibility of creating such a reactor.*"

The letter assigned the following charge:

"*Cde. Vannikov will travel together with Cdes. Kurchatov, Artsimovich, Golovin and Meshcheryakov to KB-11 and will carefully discuss, together with Cdes. Khariton, Tamm and Sakharov, and possibly other key leading researchers of the bureau that could be useful in the discussions, the proposals of Cdes. Tamm and Sakharov and will prepare a draft decision on the implementation of the required research and experimental design work along the lines suggested by Cdes. Tamm and Sakharov...*"

Further on L P Beriya emphasized:

"*In view of the especially secret nature of developing a new type of reactor, it is required that the participants be carefully selected and appropriate security be provided for this work.*

I request that the draft decision be prepared without delay and be completed, if possible, within 10 or at most 15 days."

In accordance with L P Beriya's instruction, a number of scientific and technical meetings took place at KB-11 from **January 30 to February 3, 1951** on MTR problems, involving I V Kurchatov, Yu B Khariton, I E Tamm, A D Sakharov, I N Golovin, L A Artsimovich, M G Meshcheryakov, N N Bogolyubov, K I Shchelkin, and Ya B Zel'dovich [6, Ll. 17 – 25]. The recommendations and the work schedule were proposed and then discussed in the First Main Directorate by B L Vannikov, A P Zavenyagin, I V Kurchatov and N I Pavlov.

On March 8, 1951, the first draft of the USSR Council of Ministers Resolution to organize the work on clarifying the feasibility of MTR construction was presented to L P Beriya [6, Ll. 17 – 25].

On April 5, 1951, I V Stalin approved the already mentioned Order of the USSR Council of Ministers to start building a laboratory model of a magnetic thermonuclear reactor — the MTR-L facility (prepared during February and March of 1951 in accordance with the letter of I V Kurchatov, I N Golovin and A D Sakharov of January 11, 1951) [6, Ll. 1, 2].

On April 7, 1951, a modified project of the Resolution of the USSR Council of Ministers on organizational work needed to clarify the feasibility of MTR was submitted to L P Beriya [6, Ll. 39 – 85]. On April 14, L P Beriya accepted this project, as we see from his resolution on page 1 of the project.

On April 28, 1951, a meeting of the USSR Council of Ministers Special Committee was convened that adopted the decision: "*To adopt the project of the Resolution of the USSR Council of Ministers "On conducting research and experimental work to clarify the feasibility of building a magnetic thermonuclear reactor" presented by Cdes. Zavenyagin, Kurchatov, Pavlov and Golovin and submit it for the approval of the Chairman of the USSR Council of Ministers comrade I V Stalin*" [7, L. 93].

I V Stalin approved the project of the Resolution of the USSR Council of Ministers on **May 5, 1951**.

5. On the layouts of a controlled thermonuclear reactor and lithium – hydrogen bomb, suggested by O A Lavrent'ev, and A D Sakharov's referee report on them

Let us turn to L P Beriya's letter of January 14, 1951. The final part of the letter mentioned O A Lavrent'ev:

"*Among other things we should not forget about a Moscow State University student Lavrent'ev*[8], *whose notes and proposals served, as stated in Cde. Sakharov's suggestions, as a primer in developing a magnetic reactor* (*these notes were in the First Main Directorate with Cdes. Pavlov and Aleksandrov*[9].)

I received Cde. Lavrent'ev. Judging by what I could observe, he is a very capable man. Invite Cde. Lavrent'ev, hear him out and, together with Cde. Kaftanov S V[10], *do everything necessary to help Cde. Lavrent'ev in his studies, engaging him as much as possible in this work. To be implemented within five days.*"

We see, therefore, that as early as January 1951 an official document referring to A D Sakharov's statement acknowledged that the work written by O A Lavrent'ev and sent on his request from Sakhalin to Moscow on July 29, 1950 triggered the research effort in the USSR on the problem of building a magnetic thermonuclear reactor.

In view of the priming role played by O A Lavrent'ev's work in launching research on a controlled thermonuclear reactor in the USSR, the content of the paper is undoubtedly

[8] In 1950, O A Lavrent'ev was demobilized from the army, travelled from Sakhalin to Moscow and enrolled in the Physics Faculty of the M V Lomonosov Moscow State University.
[9] A S Aleksandrov was a deputy head of the First Main Directorate.
[10] S V Kaftanov, the Minister of Higher Education of the USSR.

of great interest to the scientific community. Of similar interest is the report written by A D Sakharov on August 18, 1950 after refereeing this paper. The text of O A Lavrent'ev's work and A D Sakharov's report on it are published in the Section "From the Archive of the President, Russian Federation".

Sakharov's report focuses on an important aspect of Lavrent'ev's proposals that deals with the facility for implementing a controlled fusion reaction. The fusion reaction was to take place "*in high-temperature gas* (*billions of degrees*) *of such low density that the existing materials could withstand the resulting pressure*". A D Sakharov also analyzed another significant aspect of Lavrent'ev's proposals: the conjecture that it would be possible to extract the energy of nuclei that they gain in the process of thermonuclear combustion, using an electrostatic field which at the same time is meant to confine the nuclei in the reaction zone. A D Sakharov emphasized the difficulty of thermal insulation of the gas using electrostatic fields but remarked: "*however, it cannot be excluded that certain changes in the project may correct this difficulty*". A D Sakharov mentioned the need for detailed discussion of Lavrent'ev's project. He stressed that "*regardless of the results of the discussion, it is necessary at this point not to overlook the creative initiative of the author*".

The paper that O A Lavrent'ev sent to Moscow in the summer of 1950 contained not only the proposal for implementation of controlled thermonuclear reaction but also proposed the design of a lithium – hydrogen bomb.

As regard the lithium – hydrogen bomb, the gist of O A Lavrent'ev's proposal was the blasting of the gun-type plutonium atomic bomb in a medium consisting of lithium and hydrogen. Lavrent'ev described the principle of the lithium – hydrogen bomb in the following manner: "*In order to accelerate lithium and hydrogen nuclei to the necessary initial velocity, we can make use of the chain reaction between plutonium nuclei. The simplest way to achieve this is to explode an atomic bomb in a medium consisting of 87.5 percent lithium and 12.5 percent hydrogen. Lithium hydride is very convenient in this respect because it forms a solid. Fast particles produced in large numbers by the explosion of the atomic bomb will impart their energy to the lithium and hydrogen nuclei, which will then interact via a fusion reaction. This reaction will be explosive in nature, a more powerful explosion than that of the atomic bomb*".

O A Lavrent'ev then wrote that the design of the lithium – hydrogen bomb is "*relatively simple. The bomb consists of a detonator* (*a conventional atomic bomb*) *surrounded by a layer of lithium-6 deuteride, i.e. a compound of* Li^6 *and* H^2 *isotopes. The amount of this 'explosive' is determined by the desired power of the bomb*". O A Lavrent'ev conjectured that not only lithium-6 deuteride but also lithium-7 hydride could be used in the lithium – hydrogen bomb. However, he remarked: "*I must add that the first layers directly adjacent to the atomic bomb must consist of the isotopes* Li^6 *and* H^2. *This would require considerably more time and expense but would guarantee success because, firstly, the nuclear reaction between the nuclei* Li^6 *and* H^2 *has roughly a 30-fold yield* (*this is based on British sources*); *secondly, it is more energy-intensive; thirdly,* Li^6 *nuclei will react with neutrons* (*note, however, that this reaction gives only one fourths of the energy produced in the* $\mathrm{Li}^6 + \mathrm{H}^2 = 2\mathrm{He}^4$ *reaction*)".

In his report, A D Sakharov referred to O A Lavrent'ev's proposals on the lithium – hydrogen bomb as suggesting employment of "*nuclear reactions of the types* $\mathrm{Li}^7 + \mathrm{H}^1 = 2\mathrm{He}^4$ *and* $\mathrm{Li}^6 + \mathrm{H}^2 = 2\mathrm{He}^4$ *under the conditions of a thermal explosion* (*produced by blasting of an atomic bomb*)", but not a hydrogen bomb design. A D Sakharov emphasized that these reactions "*<u>are not</u> the most suitable during conditions of a thermal explosion because their effective cross sections at the temperatures achievable in an atomic explosion are too low*".

Indeed, the lithium – hydrogen bombs that were actually created achieved thermonuclear burning on the basis of a chain of nuclear – neutron and nuclear reactions

$$\mathrm{Li}^6 + \mathrm{n} = \mathrm{He}^4 + \mathrm{H}^3\,,$$
$$\mathrm{H}^3 + \mathrm{H}^2 = \mathrm{He}^4 + \mathrm{n}\,,$$

and also

$$\mathrm{H}^2 + \mathrm{H}^2 = \mathrm{He}^3 + \mathrm{n}\,,$$
$$\mathrm{H}^2 + \mathrm{H}^2 = \mathrm{H}^3 + \mathrm{H}^1\,,$$
$$\mathrm{He}^3 + \mathrm{n} = \mathrm{H}^3 + \mathrm{H}^1\,.$$

As for the reactions $\mathrm{Li}^6 + \mathrm{H}^2 = 2\mathrm{He}^4$ and $\mathrm{Li}^7 + \mathrm{H}^1 = 2\mathrm{He}^4$, they play only secondary roles owing to their low cross sections.

Of course, O A Lavrent'ev's proposal (1950), made quite independently, for the use of lithium-6 deuteride in a hydrogen bomb deserves our attention and even awe but an objective evaluation of this proposal cannot be made without a side remark that, proposing to use lithium-6 deuteride as thermonuclear fuel in a hydrogen bomb, O A Lavrent'ev did not point to the chains of the neutron – nuclear and nuclear reactions (given above) which in reality determined the efficiency of lithium-6 deuteride as thermonuclear fuel.

The low efficiency of O A Lavrent'ev's lithium – hydrogen bomb was obvious to specialists and did not allow A D Sakharov to treat Lavrent'ev's proposal as that of a design of a hydrogen bomb. In this connection we need to emphasize again that lithium-6 deuteride in the layout of the lithium – hydrogen bomb, given in the original manuscript of O A Lavrent'ev of 1950, was not surrounded by any shell (a construction shell may have been meant implicitly but no functional shell taking part in physical processes occurring during the bomb explosion was present in O A Lavrent'ev's layout, nor did he anticipate one).

Notice that in accordance with the USSR Council of Ministers Resolution No. 827-303ts/sd of February 26, 1950, enacted as a response to USA President Truman's directive to continue the creation of the hydrogen bomb, work on the Soviet hydrogen bomb was expanding in the USSR in 1950, and priority was given to the 'layer cake' design. The thermonuclear charge RDS-6s that was being developed constituted a spherical system of alternating layers of uranium and lithium-6 deuteride (one of these layers contained tritium as well), compressed from outside by the explosion of a chemical explosive [3, 4].

In 1993, O A Lavrent'ev published a preprint "On the history of nuclear fusion in the USSR" [8]. The way he presented his own proposals in this preprint greatly differs, as far as the lithium – hydrogen bomb is concerned, from the description of his proposals in the original paper that he sent from Sakhalin Island in summer 1950.

O A Lavrent'ev wrote in this preprint [8]:

"*I first had the idea of using thermonuclear synthesis in winter 1948. The commanding officers of the regiment instructed me to prepare a lecture for the military personnel of* *the regiment on the atomic problem. It was then that 'quantity made transition to the quality'. Having several days to prepare a lecture, I was able to rethink an entire set of accumulated data and found the solution of the problems that had occupied me for many years; I found the material that would be capable of detonating in response to an atomic explosion and also capable of magnifying it greatly — lithium-6 deuteride, and also invented a scheme in which nuclear reactions could be used for industrial purposes.*

I stumbled on the idea of the hydrogen bomb while searching for new nuclear chain reactions. I scrutinized various versions one by one and then found what I needed. The chain with lithium-6 and deuterium did close on itself relative to neutrons. A neutron colliding with a lithium-6 nucleus causes the reaction

$$\mathrm{n} + \mathrm{Li}^6 = \mathrm{He}^4 + \mathrm{T} + 4.8\ \mathrm{MeV}.$$

The triton interacting with a deuterium nucleus as

$$\mathrm{T} + \mathrm{D} = \mathrm{He}^4 + \mathrm{n} + 17.6\ \mathrm{MeV}$$

returns the neutron back to the pool of interacting particles.

The rest was a matter of technique. In Nekrasov's two-volume Course of Inorganic Chemistry I found the description of hydrides; that is, I found that deuterium and lithium-6 can be bound chemically into a stable solid with a melting temperature of about 700 degrees Celsius. In order to start the process, a high-power pulsed neutron flux is necessary, and this is produced when an atomic bomb explodes. This flux not only gives rise to numerous reaction chains in $\mathrm{Li^6D}$ *but also brings about the release of the enormous amount of energy required to heat the material to thermonuclear temperature.*

The problem yet unsolved was that of confining the substance during the time of thermonuclear combustion. Mechanics helped me in this problem. An inertial mass subjected to very large force for very short time remains motionless over that interval. The external shell must be made very massive, from a material with high specific weight. This shell would also serve as a reflector for the neutron flux and would therefore increase the efficiency of the explosion..." [8, pp. 3, 4].

When describing the contents of his papers sent to Moscow in July 1950, O A Lavrent'ev in his preprint [8] added the following outline of the constructive features of the lithium – hydrogen bomb that he suggested to his description: "*The uranium detonator was a gun type system with two subcritical hemispheres of* U^{235} *which are propelled towards one another. The symmetric arrangement of the charges was meant to increase the collapse rate of the critical mass by a factor of two in order to avoid premature matter expansion before the explosion. The uranium detonator was placed at the center of a sphere filled with lithium-6 deuteride. The massive shell was to ensure inertial matter confinement during the time of thermonuclear combustion. I also gave the evaluated power of the explosion, the method of lithium isotope separation, and an experimental program for the implementation of the project...*" [8, p. 12]. O A Lavrent'ev also added to this description a schematic diagram of a lithium – hydrogen bomb in which, judging by geometric parameters, a massive shell was placed above the layer of lithium-6 deuteride [8, p. 13].

In reality, as we mentioned above, the original proposal of the lithium – hydrogen bomb by O A Lavrent'ev did not contain any shell in the design of the bomb. Suggesting the use of lithium-6 deuteride in this bomb, O A Lavrent'ev did not count on neutron – nuclear reactions in which "*a chain with lithium-6 deuteride closed on itself relative to neutrons*" and never mentioned these reactions. Let us also note that O A Lavrent'ev's original scheme of 1950 had the active fissile material hemispheres brought in contact in a gun type atomic bomb, and not by a counter shot but by a unilateral shot. For the fissile material, O A Lavrent'ev suggested plutonium-239, not uranium-235.

In addition to this layout of the hydrogen bomb, O A Lavrent'ev's preprint of 1993 gives and discusses another schematic diagram of implosion type hydrogen bomb, in which a sphere made of lithium-6 deuteride is surrounded by shells of plutonium-239 and a spherical layer of chemical explosive [8, pp. 17, 18]. This, just as the former one, is dated July 1950. The preprint states that this scheme was also proposed by O A Lavrent'ev while on Sakhalin, but after his work was already sent to Moscow. It is clarified that the idea of the new design appeared to O A Lavrent'ev while travelling to Moscow to enroll in Moscow State University. In the Sakhalin regional committee of the Party, where he asked for help with transportation problems, he was given a chance to read a book by H D Smyth [9]. O A Lavrent'ev wrote in his preprint [8]: "*It is a pity that I never saw this book before. I found there a detailed description of the work done in the American atomic project and answers to many of my questions that I had had to hit myself. The most important thing, however, was that in the book I found a description of the method of creating a critical mass by implosion, i.e. by a cumulative explosion that compresses a thin spherical shell of plutonium towards the center. This gave me an idea for a new layout of a hydrogen bomb. Since the center was already occupied by lithium-6 deuteride, I enclosed it in a thin plutonium envelope of subcritical mass. Another plutonium envelope with a greater diameter was sent collapsing onto the first, forming an above-critical mass... This Yuzhno-Sakhalinsk version left me in no doubt that I was on the right path.*"

Commenting on O A Lavrent'ev's story about the second of the proposed layouts of a lithium – hydrogen bomb, it is first of all necessary to emphasize that the implosion principle was not laid down in H D Smyth's book [9] and is never even mentioned there. Nor could this principle be discussed in any other open publications, owing to its absolute top-secret status at the time. H D Smyth wrote in the book that the "*the bomb must consist of a number of separate pieces each one of which is below the critical size either by reason of small size or unfavorable shape. To produce detonation, the parts of the bomb must be brought together rapidly. In the course of this assembly process the chain reaction is likely to start — because of the presence of stray neutrons —* before *the bomb has reached its most compact* (*most reactive*) *form. Thereupon the explosion tends to prevent the bomb from reaching that most compact form. Thus it may turn out that the explosion is so inefficient as to be relatively useless... Since estimates had been made of the speed that would bring together subcritical masses of U-235 rapidly enough to avoid predetonation, a good deal of thought had been given to practical methods of doing this. The obvious method of very rapidly assembling an atomic bomb was to shoot one part as a projectile in a gun against a second part as a target*" [9, pp. 211 – 212]. We see that this description has a long way to go to rate as a description of implosion. At the same time, H D Smyth's book was very detailed in treating the role played by the envelope: "*In a uranium – graphite chain-reacting pile the critical size may be considerably reduced by surrounding the pile with a layer of graphite, since such an envelope 'reflects' many neutrons back into the pile. A similar* *envelope can be used to reduce the critical size of the bomb, but here the envelope has an additional role: its very inertia delays the expansion of the reacting material. For this reason such an envelope is often called a tamper. Use of a tamper clearly makes for a longer lasting, more energetic, and more efficient explosion. The most effective tamper is the one having the highest density; high tensile strength turns out to be unimportant. It is a fortunate coincidence that materials of high density are also excellent as reflectors of neutrons*" [9, p. 210].

No documents were found that would confirm that the implosion-type lithium – hydrogen bomb layout given by O A Lavrent'ev in his preprint [8, p. 18] as the scheme that he proposed in 1950 could indeed be dated to 1950. According to O A Lavrent'ev, he, already a student of the Physics Department of Moscow State University, was received in September 1950 by I D Serbin to whom he had earlier sent his paper from Sakhalin. "*I D Serbin asked me to describe in detail my proposals for the design of the hydrogen bomb. He heard me out very attentively, never interrupted me, asked no questions, and at the end of this conversation told me that a different method of creating a hydrogen bomb is known and that our scientists work on this other method. Nevertheless, he suggested that I keep in touch and inform him of any new ideas that I might have*" [8, p. 19]. After this meeting with I D Serbin, O A Lavrent'ev wrote his second paper and had it forwarded to I D Serbin at the very end of 1950 via CC CPSU dispatch office [11]. This paper contained no description of an implosion type lithium – hydrogen bomb (O A Lavrent'ev's second paper was devoted to improving his layout of a thermonuclear reactor with an electrostatic field: instead of a single grid creating such a field, the new design suggested two or three) [6, Ll. 88 – 95]. No other papers or proposals made at that time were found in the Archive of the President, Russian Federation, only the two papers that we have already discussed — one sent on July 29, 1950 from Sakhalin Island and the other written at the end of 1950 in Moscow.

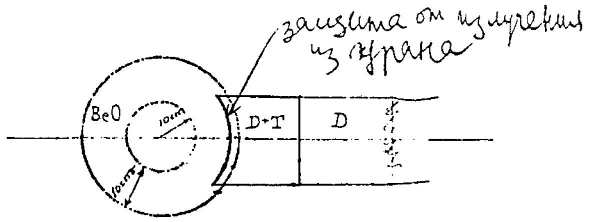
6. A few words about the initial period of research into the feasibility of creating a thermonuclear reactor in the West

The pattern of events that preceded the moment when A D Sakharov suggested his idea of magnetic thermal insulation of the plasma would be incomplete if we failed to describe a fact that became known only in recent years.

On 19 September 1945, Klaus Fuchs (a physicist of German origin who in 1944 – 1946 worked as a member of the British team in Los Alamos and collaborated with Soviet intelligence) met in Santa Fe with Harry Gold and passed to him a synopsis of Enrico Fermi's lectures; the lectures presented the theoretical foundation of the American project for the hydrogen bomb known as the 'classic super' and which reflected the earlier approaches of scientists at Los Alamos to the problem of building the hydrogen bomb [3, 4]. For the basic layout of the 'classic super', the lectures considered the combination of a gun type atomic bomb, an intermediate chamber with a deuterium – tritium mixture, and a cylinder with liquid deuterium. An interesting feature of this document was that one of the suggested ways to initiate thermonuclear combustion was to use a magnetic field to reduce plasma thermal conductivity [10, p. 108]. The synopsis of Enrico Fermi's lectures had a section on the "Use of magnetic field to reduce heat conductivity". The lecturer noted that since the time scale for the ignition is very long, thermal conduction may lead to serious losses. Applying magnetic field could reduce these losses. The concluding part of the document said:

"*So far, all schemes for initiation of the super are rather vague. The one in highest favor is as follows: At the center is a 25 gadget* [12] (*about 100 kg of '25'*), *shot together by a gun. It is surrounded by a BeO tamper which has good neutron reflection properties and is transparent for radiation. Part of the surface of the* BeO *is covered with Tuballoy* [13] *as a shield against radiation and behind this shield is a* D + T *mixture, which is heated by the neutrons escaping from the gadget.*

If a magnetic field is used, the D + T *mixture might be in the form of an annular* (i.e. toroidal — *Auth.'s note*) *ring, so that only the transverse heat conductivity matters. Beyond the* T + D *mixture is pure D* [14].



Correct: (signature) /Gorelik/
Processed by: (signature) /Terletskiĭ/
January 28, 1946."

Note that the hand written text ('*Tu radiation shield*' in English) on the diagram was made by Ya B Zel'dovich.

We see that the idea of magnetic thermal insulation in Fermi's lectures referred to one of the earliest projects of the hydrogen bomb. The question then arises: did the scientists at Los Alamos consider the possibility of making a controlled thermonuclear reactor at the time when Fermi's lectures were prepared? If the answer is yes, then did anybody suggest the idea of plasma magnetic thermal insulation in a thermonuclear reactor? Did they think of creating a toroidal thermonuclear reactor? All these questions are answered in a paper "Magnetic fusion" by James Phillips [11]. We shall quote from this article:

"*During the war years while the Laboratory was thinking about ways to use nuclear energy to create violent explosions, Ulam, Fermi, Teller, Tuck and others were also thinking about fusion of the light elements for the controlled release of energy and the production of useful power.*

It had been understood since the 1930s that the source of energy in the sun and other stars is thermonuclear fusion occurring in the very hot plasmas that make up the stars' centers. The thermal energy of the nuclei in these plasmas is so high that positively charged nuclei can penetrate the Coulomb barrier and approach so closely that fusion can occur.

To duplicate this process in the laboratory requires creating a plasma, heating it to thermonuclear temperatures, and confining it long enough for fusion reactions to take place. By

[11] O A Lavrent'ev's second paper was entered into the books of the Secretariat of the CPSU Central Committee on December 23, 1950. I D Serbin transferred it on January 2, 1951 to the Secretary of the Special Committee, V A Makhnev.

[12] '25' denoted uranium-235.

[13] 'Tu' or Tuballoy was a code word for uranium in the documents of the period.

[14] Liquid D in a long cylindrical vessel — *Auth.*

1946, the Los Alamos group concluded that the plasma would have to be heated to about 100 million degrees Celsius — ten times hotter than the sun's center and many orders of magnitude higher than any temperature yet achieved on Earth.

Since a plasma that hot would quickly vaporize the vacuum container in which the plasma is created, some means for preventing the plasma's contact with the container walls was required. A 'magnetic bottle', i.e. a magnetic field of appropriate strength and geometry, was a possibility. A cylindrical magnetic bottle could be produced, but the plasma particles would quickly be lost out the ends. On the other hand, a toroidal, or doughnut-shaped, bottle would eliminate end losses but, as Fermi pointed out, particles in a simple toroidal magnetic field will rapidly drift outward and strike the walls.

Calculations of the energy released by thermonuclear reactions versus the energy loss through radiative and other processes were also done in those early days. The conclusion was that in terms of energy balance a power reactor based on nuclear fusion was not impossible."

We see that scientists at Los Alamos did not restrict themselves to considering the potential use of magnetic thermal insulation for the initiation of a hydrogen bomb and also mulled this idea in 1946 with respect to perhaps implementing it for the fusion of light elements under laboratory conditions. The idea of resorting to magnetic thermal insulation to initiate the 'classical super' was dropped but the possibility of ultimately creating a thermonuclear power reactor was not discarded as hopeless [15].

New hopes emerged once the idea of magnetic plasma confinement by running an electric current along the axis of the reaction chamber was proposed:

"*In 1950 Jim Tuck returned to Los Alamos* (*after a sojourn in his native England and at the University of Chicago*) *and began working on magnetic confinement with a 'Z-pinch'. In this scheme an electric field applied along the axis of a discharge tube causes an electric current whose self-magnetic field pinches the current channel toward the axis of the tube. It was thought that the pinching process would produce the high plasma densities and temperatures necessary for fusion. Tuck knew from the work of British scientists that building up the current rather rapidly to create high temperatures caused instabilities in the pinch. He suggested that the instabilities might be minimized by applying a small electric field across the length of the discharge tube and increasing the current slowly. In addition he wanted to try this slow* Z*-pinch in a toroidal discharge tube*."

It is impressive how close were the ideas of the Soviet and American (as well as British) scientists at the very first stages of research into controlled nuclear fusion.

Ever since 1951, this work has been supported and scheduled in the USSR by ad-hoc governmental decrees, the first of which, as described above, were passed in April and May 1951. The history of events that led to their enactment is told in this article. After these governmental decrees were enacted, they were followed by a long-term theoretical and experimental search for ways to solve this problem — a problem of grandiose potential that proved to be one of exceptional complexity. Intervals of promising results (the first of which was the discovery of neutron emission on the experimental facility at the Kurchatov Institute on July 4, 1952; the neutrons were initially erroneously identified as originating from fusion reactions [12, L. 87]) alternated with long intervals of disappointment.

The history of this research and the current state of affairs are discussed in the article by V D Shafranov.

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[15] The translation of this paragraph follows the corrigenda that will appear in issue 10 (2001) of this journal: *Usp. Fiz. Nauk* **171** (10) 1148 (2001) — *Translator's Note.*