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Role played by O A Lavrent'ev in the formulation of the problem and the initiation of research into controlled nuclear fusion in the USSR

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1. Introduction

It is of interest, in the reconstruction of the 50-year-old history of nuclear fusion research in the USSR, to describe in detail the role played by a young Red Army soldier O A Lavrent'ev, who in the late 1940s and early 1950s served in the army on Sakhalin Island, in initiating and expanding the research in controlled nuclear fusion (CNF) in the USSR and also about his proposal for the design of the hydrogen bomb.

The father of the hydrogen bomb in the Soviet Union is without doubt A D Sakharov. The first row of creators of atomic and hydrogen bombs also includes I V Kurchatov (scientific leader of the nuclear programs), I E Tamm, Yu B Khariton, Ya B Zel'dovich, K I Shchelkin, and E I Zababakhin. Recently added to this list was the name of V L Ginzburg [after his proposal for using lithium-6 deuteride (^{6}LiD) in the hydrogen bomb was declassified].

It must be noted that the proposal to use a solid chemical compound (briquetted ^{6}LiD) as the main nuclear fuel in the hydrogen bomb instead of the earlier plans oriented at using liquefied deuterium was one of the most important factors that subsequently allowed the design of a sufficiently compact transportable hydrogen bomb with practically unlimited explosive power. The use of liquefied deuterium as the main fuel would require cumbersome cryogenic technology, which would make this type of bomb practically non-transportable.

Sufficiently many reviews have been written on the history of creation of the atomic and hydrogen bombs in the USSR [1 – 6]; even monographs exist [7]. If we ignore for the moment the theft of classified Western data, the role of Soviet scientists in these sources is described with sufficient objectivity. The same cannot be said about the history of CNF research in this country. The founders of CNF with the magnetic confinement of hot plasma in thermonuclear reactors are believed to be A D Sakharov and I E Tamm. This is true of course but the fact that the name of O A Lavrent'ev is practically never mentioned in this context is certainly unfair.

This paper is an attempt to repair this injustice and to describe the role that O A Lavrent'ev played both in initiating and advancing the CNF program and in the design of the hydrogen bomb in this country.

My first statement will be that the first person in the USSR to formulate this problem and to suggest a certain constructive solution to it in the middle of 1950 was a young soldier, Oleg Aleksandrovich Lavrent'ev, who at the time was serving in the army on Sakhalin Island.

His proposal, which contained two major ideas, was mailed by secret special delivery to Moscow on July 29, 1950 and was addressed to the Central Committee of the Communist Party of the Soviet Union.

The first idea was the suggestion concerning a physical scenario for the hydrogen bomb. The second idea was a proposal to use a controlled thermonuclear reaction in industrial energy production. The proposal included a concrete reactor layout in which the thermal insulation of a high-temperature plasma was achieved by a high-voltage electric field.

These suggestions were passed on in Moscow to the leading nuclear scientists [1]. The responses to this work emphasized Lavrent'ev's priority, and his original and bold thinking. This work stimulated new projects by other researchers: the MTR (magnetic thermonuclear reactor), TOKAMAKs [TOroidal chambers (KAmery in Russ.) with MAgnetic coils (Katushki in Russ.)], magnetic 'bottles' — 'probkotrons' and so on. O A Lavrent'ev, later in Moscow and then in Khar'kov, continued to improve his model of the so-called 'electromagnetic trap'.

2. Ya B Zel'dovich on O A Lavrent'ev and his CNF proposal

I first heard O A Lavrent'ev's name in 1958, on the Semipalatinsk bomb testing grounds. The Ministry of Medium-Scale Engineering Industry (MSM in Russ. abbr.) and the All-Union Research Institute of Experimental Physics (VNIIÉF) were then conducting a series of tests of nuclear charges; the theoretical aspects of these charges were the responsibility of my Department No. 3 forming a part of the Division No. 2 headed by Ya B Zel'dovich. My boss, Ya B Zel'dovich, a Full Member of the Academy of Sciences of the USSR (Academician for short), and myself were then the science representatives in the State Commission on the tests.

At the time, the Semipalatinsk testing grounds housed, among other systems, a school to train officers in the art of technical maintenance of nuclear warheads (nuclear ammunition) over their entire service cycle, from the manufacturing stage at a regular plant to the battle station on a launching pad.

The commanding officers of the testing grounds (I N Gureev and V M Barsukov) suggested to Ya B Zel'dovich to deliver a popularizing lecture to the entire officer corps of the testing grounds garrison on nuclear weapon and nuclear power engineering. Ya B Zel'dovich accepted the suggestion: he liked to popularize science, he did it with obvious pleasure and wonderful skill.

Yakov Borisovich was an exceptional speaker, of great erudition and excellent sense of humor. The lecture hall of the

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[1] See A D Sakharov's referee report included in this issue in the Section "From the Archive of the President, Russian Federation" [*Phys. Usp.* **44** 859 (2001)]

Officers' Club was full to capacity. I think there may have been three hundred people in the hall.

Among other things, Ya B Zel'dovich touched on the circumstances in which Andreĭ Sakharov got his idea for the magnetic thermonuclear reactor in 1950. The story was very new to me. Here is what Ya B Zel'dovich told us on that day:

In the 1950s, a soldier with seven years of schooling, Oleg Aleksandrovich Lavrent'ev, was doing military service on Sakhalin Island. In early 1950, he wrote a letter to I V Stalin suggesting to use the nuclear fusion reaction of heavier hydrogen isotopes, deuterium and tritium, for peaceful power engineering. The principal idea of his suggestion was to prevent the ions of the high-temperature thermonuclear plasma from reaching the reactor walls using an electric field.

Then Yakov Borisovich said that O A Lavrent'ev's suggestion was forwarded from the Central Committee of the CPSU in the middle of 1950 to A D Sakharov for evaluation; Sakharov was at that time a PhD (Candidate of Sciences) and he praised the proposal very highly. He actually said that the proposal was very interesting indeed, bold and original.

The soldier O A Lavrent'ev was invited to Moscow. At that moment he was already a junior sergeant and Zel'dovich and Sakharov helped him to get a university education.

Lavrent'ev's idea for preventing the high-temperature plasma from reaching the reactor walls using an electric field led A D Sakharov to the idea of magnetic high-temperature plasma confinement. The next step was A D Sakharov's and I E Tamm's proposal (1950) to develop a toroidal model of a magnetic thermonuclear reactor (MTR) which later evolved into the 'tokamak'. This point of view was described by Ya B Zel'dovich in his science-popularizing lecture.

The MTR research and development began at LIPAN (currently the Russian Research Centre 'Kurchatov Institute') in 1951 and were led by I V Kurchatov's first deputy I N Golovin; scientific leadership was provided by A D Sakharov (on short visits from Sarov). The experimental part of the CNF program was headed by L A Artsimovich, and the theoretical part by M A Leontovich.

After this, I happened to have several meetings with O A Lavrent'ev. We had long and exciting conversations. His descriptions of how it all had happened and of how things unfolded later were very interesting and in some points highly instructive. We talked for hours, recalling the days gone by. Oleg Aleksandrovich Lavrent'ev now lives in Khar'kov, enjoys good health, works at the Plasma Physics Institute of the Khar'kov Physico-Technical Institute. He has published more than a hundred papers in a number of languages and registered several dozen of inventions. He also described his role in the creation of the hydrogen bomb and the CNF problem in an IOF RAN preprint No. 8 (1993) [8].

However, the way he told it was somewhat different from the narrative of Ya B Zel'dovich. I will describe below the impressions I had from those long conversations with Lavrent'ev.

The story told by Yakov Borisovich in his lecture has survived in my memory. Of course, it was interesting and highly unusual: a soldier in the army, after just seven years of school, writes a letter to I V Stalin from Sakhalin Island, is invited to Moscow, and prompts A D Sakharov and I E Tamm to their invention of the MTR. And this was only the beginning!

3. O A Lavrent'ev's story about himself and about his proposals with Bondarenko's comments

O A Lavrent'ev was born on July 7, 1926 in Pskov into a family of peasant origin who, after the 1917 revolution, abandoned country life and moved to the city. His father, Aleksandr Nikolaevich, had all kinds of different jobs. His mother, Aleksandra Fedorovna, was a nurse. At the age of 18, O A Lavrent'ev volunteered for the army. He took part in battles in the Baltic states in 1944 – 1945, was awarded medals 'For victory over Germany' and 'On the 30th Anniversary of the Soviet Army'. When the Second World War was over, he was transferred to the Sakhalin military district. He first learned of nuclear physics in 1941, then in the 7th grade of a secondary school. He read science publications and textbooks on nuclear physics that were published in the USSR before the war with German fascists. He then learnt about the uranium problem, about the possibility of initiating a nuclear chain reaction involving ^{235}U isotopes, about the need for ^{238}U and ^{235}U isotopes, and about the isotope separation methods. All this excited him so much that he decided to devote his life to this occupation.

The war disrupted all his plans and took him away from his studies for several years. However, once he was transferred to Sakhalin, the situation grew more favorable. His rank rose to a sergeant and he worked as a radiotelegraph operator. He started to get paid, subscribed to *Soviet Physics-Uspekhi* (*UFN*) and obtained a number of other physics monographs and textbooks; he started to borrow technical literature from the library of his regiment. He studied mechanics, molecular physics, electricity and magnetism, nuclear physics and delivered reports to the officer corps on the latest news in military technology.

The idea of using thermonuclear synthesis for industrial purposes first grew on him, as Oleg Aleksandrovich told his listeners, in winter 1948 when he was preparing a lecture for the officers on the nuclear problem. He and two more soldiers were allowed at that time to attend evening classes for working youth. In May 1949, he graduated from school, having covered three grades in one year.

In January 1950, the President of the United States Harry Truman, speaking to the US Congress, called on the scientists of the United States to speed up the work on the hydrogen bomb [2]. This prompted O A Lavrent'ev to make the next step.

O A Lavrent'ev said later that, having read and analyzed a plenty of available open publications, he was sure even then that he knew how to produce a hydrogen bomb and he was certain that it would definitely explode. He then wrote a short letter to Stalin, declaring that he knew the secret of the hydrogen bomb. O A Lavrent'ev *never received* a reply to that letter; as he commented it in our conversation, his letter had most likely drowned in the flood of congratulations to I V Stalin in connection with his 70th anniversary on 21 December 1949.

Several months later, he wrote a very similar letter to the CPSU Central Committee. The response to this letter was rapid. After a call from Moscow to the Sakhalin regional party committee, the latter ordered that O A Lavrent'ev be assigned a separate guarded room on the grounds of his

[2] This was his response to the first Soviet atomic bomb test on August 29, 1949 (the RDS-1 atomic bomb or JOE-1, as Americans used to refer to it).

Junior sergeant of the active service (radiotelegraph operator), Oleg Aleksandrovich Lavrent'ev (Sakhalin Island, 1950).

regiment, where he was to write his first paper on thermonuclear synthesis.

The work principally presented two key ideas.

The first idea was a description of the principle of a hydrogen bomb with lithium-6 deuteride as the main nuclear fuel and with uranium detonator constructed on the model of head-on collision of gun-barrel-propelled subcritical masses of fissile material. The uranium detonator was at the center of a sphere filled with ^{6}LiD.

The second idea was a proposal for the design of an industrial thermonuclear reactor. The reactor was a system of two spherical concentric electrodes. The inner electrode was to be a transparent grid, and the outer electrode was to be an ion source. The grid was to be at high negative potential. The plasma is created in this system by the injection of ions from the surface of the outer sphere and by the emission of secondary electrons from the grid. The plasma was assumed to be thermally insulated by the retardation of ions in an external electric field. As a result of focusing the deuterium ions at the center of the sphere, the plasma density there reaches a maximum and intense thermonuclear 'combustion' occurs. Near the negative grid, the plasma density falls off by several orders of magnitude. The fusion reaction there is very weak, thermal loss is insignificant and the grid is not destroyed.

This was how the plasma thermal insulation was to be achieved in O A Lavrent'ev's scheme.

All this was taking place still on Sakhalin Island. The paper was written as a single hard copy (the draft versions were destroyed) and delivered by secret mail delivery service on July 29, 1950 to the CPSU Central Committee, addressed to the Head of the Department of Heavy Engineering Industry, I D Serbin (see the Section "From the Archive of the President, Russian Federation").

On O A Lavrent'ev's request, he was demobilized before the end of service and travelled via the town of Yuzhno-Sakhalinsk to Moscow to enrol in Moscow State University to which he had already sent an application.

He was warmly welcomed by the regional party committee in Yuzhno-Sakhalinsk. While he was waiting for his airplane to the town of Khabarovsk, he was given H D Smyth's report *Atomic Energy for Military Purposes* [9], which gave him extensive information on the American Manhattan project. It also stimulated an idea for a new arrangement of the implosive hydrogen bomb with ^{6}LiD at the center. The schematic diagrams of the hydrogen bomb design and the industrial fusion power reactor are given in the IOF RAS preprint No. 8 (1993) [8].

O A Lavrent'ev arrived in Moscow on August 8, 1950. He was able to pass the entrance exams at the Moscow State University (MGU) and was accepted without anybody's help. In September, when he was already a student of MGU, he met with I D Serbin. The latter requested that he write up his ideas on thermonuclear synthesis. He wrote this paper (he was writing in a classified security-protected room) and sent it to I D Serbin via the CPSU Central Committee mail delivery service [3].

O A Lavrent'ev lived at this time in a student's hostel at 32 Stromynka Street, room 603. When he returned to the hostel on January 3, 1951 in the evening, he was requested to dial a certain telephone number. He did. The person at the other end introduced himself as V A Makhnev, the Minister of Measuring-Instrument-Making Industry. Lavrent'ev learned later that Makhnev was also the secretary of a Special Committee chaired by L P Beriya. Makhnev suggested that Lavrent'ev come immediately to his study in the Kremlin. A pass was ordered for him. Another man was waiting at the check point before the Spassky tower gates of the Kremlin. They walked in together. Makhnev met them outside his office and introduced the two men. The second one was Andreĭ Dmitrievich Sakharov.

Lavrent'ev spotted his second paper, written in Moscow, on the minister's desk [4] . The paper was beautifully printed and bound. Makhnev asked Sakharov whether he had already read this work. Sakharov replied that he had not but that he had read the previous one that impressed him greatly. Makhnev recommended that Sakharov read the second one as well.

Several days later they again met in the same office. Makhnev told them that they would be received by the Chairman of the Special Committee.

[3] The Head of the Department of Heavy Engineering Industry of the CPSU Central Committee, I D Serbin, wrote to V A Makhnev in the USSR Council of Ministers: "... forwarding herewith Lavrent'ev's proposal and Sakharov's referee report, please undertake the necessary action". (Signed: "Serbin, September 27, 1950") [Archive of the President, Russian Federation (APRF) Fond 93, Delo 30/51, List 87].

[4] Listy 88 – 94 of Fond 93, Delo 30/51 in the Archive of the President, Russian Federation contain additional calculations written in O A Lavrent'ev's hand, on the CNF system (on seven pages). Serbin sent this material with his cover letter (List 95 of the archive) to Makhnev on January 2, 1951 as a complement to the first proposal.

The rest of the story is given in O A Lavrent'ev's words:

Some time later, not a very short time to be true, A D Sakharov and then myself were invited to the chairman's office.

A heavy stout man in pince-nez rose from behind the desk, came forward to meet me, shook my hand, and suggested that we sit down. He then enquired about our relatives, including relatives in prison, and so on. Nothing about current occupations. He was just sizing us up. He had seen my documents in advance. I concluded that he wanted to have a look at me, and probably at A D Sakharov, to evaluate what sort of people we were. His impressions seemed to be favorable [5].

Some time later, the privileges arrived: a larger scholarship, then a furnished room in Moscow close to the city center (32/34 M Gorky Quay) assigned by a decree of the Council of Ministers of the USSR in place of a hostel bed; delivery of any required scientific literature, additional tutors paid for from the funds of the First Main Directorate. When I and A D Sakharov left the Kremlin together, A D Sakharov said that from now on everything would go smoothly, and they would work together.

Something else happened quite soon. One night, a strongly built young man visited me at the hostel and suggested I go with him to a certain place; I followed him. We arrived at a building on Novaya Ryazanka Street, not far from Komsomol'skaya Square. We filled in a number of forms for passes into the building and this took a long time. Then we went up to the office of N I Pavlov on the second floor. I discovered that they had been waiting for me there for quite a while. Then we went to another office. I read the name on the door: B L Vannikov. Two generals were in the office — B L Vannikov and N I Pavlov, and a civilian with a broad and thick black beard. In all the time I spent in the army, I never saw a general, while here there were two, plus this bearded civilian. We started a conversation. The civilian was asking the questions. I learnt later that he was I V Kurchatov.

During the conversation, Pavlov inserted a remark: "*He wishes to insert an atomic bomb into this device*"*. I became apprehensive and thought:* "*Am I allowed to discuss the design of the hydrogen bomb without special permission from the top?*" *and, involuntarily, I said that I had been to see Beriya.*

Then Pavlov took over the problem of my next placement [6]. *I would visit his office, describe my ideas, put them in writing and leave the pages with him. He would lock them in a strongbox. His kind attention to my work inspired me to more creative efforts. He introduced me to D I Blokhintsev who at that time was directing the construction of the world-first atomic power plant in Obninsk.*

Then N I Pavlov introduced me to I N Golovin, one of the leaders in the MTR work at LIPAN. I was invited to work in Golovin's group [7].

Furthermore, I was given a chance of studying additionally with university teachers: I was taught physics (by Roman Vladimirovich Telesnin, physicist, graduated from Kiev State University in 1926), mathematics (by Aleksandr Andreevich Samarskiĭ, currently a Full Member of the RF Academy of Sciences) and English.

Very good relations with A A Samarskiĭ were soon established. I am indebted to him not only for specific knowledge in mathematical physics but also for learning methodology, the knack of making a clear iron-cast formulation of a problem.

The term of interest is also the quotation from preprint [8]:

"*With A A Samarskiĭ I carried out computations of 'magnetic' grids. We deduced and solved differential equations which allowed me to calculate the magnitude of current through the turns of the grid; the grid was protected by the magnetic field of this current from bombardment by high-energy plasma particles. This work, completed in March 1951, gave rise to the idea of electromagnetic traps.*

In May 1951, I was cleared to work in LIPAN in the group of I N Golovin. Here I got acquainted with the idea of thermal insulation of a high-temperature plasma by a magnetic field, suggested by A D Sakharov and I E Tamm. I thought that they proposed this idea independently of my work done in July 1950. However, Sakharov later told me that he stumbled on this idea after reading my paper when he was asked to referee it."

[5] The Archive of the President, Russian Federation has the following report to L P Beriya in Fond 93, Delo 30/51, on Listy 98 and 99: "Following your assignment [see Beriya's letter of January 14, 1951, which is quoted in G A Goncharov's paper in *Phys. Usp.* **44** 851 (2001)] we called O A Lavrent'ev, a freshman student of the Physics Department of MGU, to the First Main Directorate. Lavrent'ev described his proposals and wishes. We consider it advisable to: 1. Assign him a personal scholarship of 600 roubles. 2. Relieve him from paying for education at MGU. 3. Assign highly skilled teachers of MGU to give O A Lavrent'ev individual tutoring: in physics — Telesnin R B, in mathematics — A A Samarskiĭ (the costs to be covered by FMD central board). 4. Assign O A L a room of 14 square meters as his living quarters in the First Main Directorate apartment block on Gorky Quay 32/34, and provide it with the furniture and the necessary scientific and technical library. 5. Pay O A L a lump sum of 3000 roubles from the First Main Directorate funds". Signed: B Vannikov, A Zavenyagin, I Kurchatov, N Pavlov.
January 19, 1951.

[6] A memorandum written on February 26, 1951 by B L Vannikov, A P Zavenyagin and I V Kurchatov is stored in the Archive of the President, Russian Federation (Fond 93, Delo 30/51, Listy 102, 103):
To comrade Beriya L P
In accordance with Your Instructions on the possible participation of O A Lavrent'ev in the research work on the MTR problem, it became clear in the recent conversations with him that he would like to concentrate on the mathematical verification of his idea of designing a power plant for direct conversion of nuclear energy into electric power, using ^{7}Li and hydrogen. However, given the colossal electric power required for this (on the order of hundreds of millions of kW) if a plant is based on light nuclei, he is forced to turn first of all to developing a 'STARTER' unit that produces electric power on the basis of fission of heavy nuclei of ^{239}Pu and ^{235}U or a mixture of them. As the research and development of problems concerning generation of industrial-scale power by 'atomic' plants is in the responsibility of the 'V' Laboratory of the First Main Directorate, we recommend that D I Blokhintsev should organize a small team of theoreticians in the Laboratory with the task of carrying out the mathematical computations required by the idea suggested by O A Lavrent'ev. For the duration of this work, O A Lavrent'ev, without interrupting his university courses, will be attached to the 'V' Laboratory as a nonstaff member. Comrades Blokhintsev and Lavrent'ev agreed to this proposal; O A Lavrent'ev finds it possible to spend five days each month in Obninsk. We request Your administrative directions." Signed: B Vannikov, A Zavenyagin, I Kurchatov. February 26, 1951.

[7] The Archive of the President, Russian Federation, F. 93, D. 30/51, L. 104 contains the following document: "To comrade Beriya L P (memorandum). As regards the trainee in the Department of Electric Equipment of LIPAN, we propose: 1. To introduce O A L into the current status of work on the MTR. 2. To permit his attendance of MTR colloquia. 3. To assign O A Lavrent'ev a consultant on gas discharges (Cde. Andrianov). 4. To permit his attendance at LIPAN on Tuesdays and Fridays, without interruption of his studies at Moscow State University (Lavrent'ev agreed)." Signed: A Zavenyagin, I Kurchatov, N Pavlov, April 24, 1951. List 105: a short note on a separate scrap of paper, roughly 4x4 cm, with a single word written on it: "Agreed" plus his personal signature "L Beriya. May 12, 1951". This is the last document covering correspondence about O A Lavrent'ev in the Archive of the President, Russian Federation, Fond 93, Delo 30/51.

The following could be added to Lavrent'ev's story.

Notice that A D Sakharov returned to the role played by O A Lavrent'ev in the CNF problem more than once. His first official referee report on the work was written on August 18, 1950 and was classified 'Top secret; Special dossier'; the second referee report was written on November 24, 1973 in relation to O A Lavrent'ev's request for the State Committee of the USSR Council of Ministers on Inventions and Discoveries and was 'not classified', and finally the third was included in A D Sakharov's book *Memoirs* (1989) [10], where A D Sakharov described his work on the CNF problem and emphasized the role played by the pioneering suggestions of O A Lavrent'ev.

In the brief reference dated November 24, 1973 [8, p. 88], A D Sakharov wrote that in June or July 1950 he reviewed the paper by O A Lavrent'ev, which greatly impressed him with its originality and courageous thinking; then he noted that in this paper the author:

(1) Proposed to use CNF for industrial purposes.

(2) Came up with a concrete scheme based on thermal insulation of high-temperature plasma by an electric field.

Sakharov emphasized [8, p. 88] that these proposals were advanced by O A Lavrent'ev on his own, independently of other authors, before anything was published on the matter.

In his *Memoirs* [10, p. 186] A D Sakharov wrote:

"*In my referee report I wrote that the idea of controlled nuclear fusion reaction suggested by the author was an extremely important one. The author invoked a problem of gigantic consequence, which meant that he was a person of initiative and creative potential, deserving all possible support and help.*

As for the specifics of Lavrent'ev's proposal, I wrote that in my opinion it was not feasible since it did not exclude direct contact of the hot plasma with the grids, inevitably leading to huge heat removal and therefore to the impossibility of implementing temperatures that would be sufficient to sustain the fusion reactions. I should have also written that it could not be excluded that the author's idea may prove fruitful in connection with some other ideas but since I had none in this respect I failed to write this phrase[8]. *The first vague ideas on magnetic thermal insulation started to form, while reading his letter and writing the referee report.*"

I N Golovin, at the time I V Kurchatov's first deputy, mentions in his memoirs that the work on peaceful applications of nuclear fusion reactions were initiated by I E Tamm and A D Sakharov after they studied a letter from a soldier Oleg Lavrent'ev in summer 1950.

I N Golovin wrote in his referee report [8, pp. 53, 54] dated 2 April 1975 and forwarded to the State Committee of the USSR Council of Ministers on Inventions and Discoveries: "*A detailed discussion in which S Yu Luk'yanov, Doctor of Physicomathematical Sciences, took part occurred in October 1951. We found no drawbacks to O A Lavrent'ev's model. Having graduated from Moscow State University, he started experiments on verifying and extending his model at the Khar'kov Physico-Technical Institute. It is too early to make a final conclusion but the progress in the experiments is obvious.*"

[8]Andreĭ Dmitrievich did not deserve this reproof. He **did indeed write** in his report: "However, changes to the project that would correct these difficulties cannot be excluded". [A D Sakharov in fact underlined this sentence in the original; see Section "From the Archive of the President, Russian Federation" (*Phys. Usp.* **44** 859 (2001)].

Sakharov discussed the issues of Lavrent'ev's letter with Tamm. As a result of these discussions, they worked out the concept of thermal insulation of high-temperature plasma using a magnetic field and calculated the draft models of a magnetic thermonuclear reactor of toroidal shape [11, 12], which subsequently evolved into 'tokamaks' [13, 15].

O A Lavrent'ev's letter was a catalyst for the emergence of the Soviet program on CNF research.

I E Tamm and A D Sakharov enlisted the cooperation of a group of theoreticians at the P N Lebedev Physics Institute (FIAN) for this work and presented the results to I V Kurchatov.

Igor' Vasil'evich Kurchatov eagerly supported this direction of research. Invoking his inexhaustible energy, goal orientation and charm, he persuaded a number of the best Soviet physicists to join this work. After reports to the government, a program of MTR research was written and submitted.

The Resolution of the USSR Council of Ministers, approved by I V Stalin, was released on May 5, 1951 and thus set in motion the state program of thermonuclear research (perhaps the first in the world). An MTR Research Council was created: chairman I V Kurchatov, deputy chairman A D Sakharov, members D I Blokhintsev, I N Golovin, Ya B Zel'dovich , M G Meshcheryakov, I Ya Pomeranchuk and Yu B Khariton (see below the Section "From the Archive of the President, Russian Federation").

The CNF research both in the USSR and in other countries was classified because the results could be relevant to solving certain military problems.

For instance, Sakharov's optimal MTR could produce, according to calculations, up to one hundred grams (!) of tritium per day [13]. Not a bad charge for a hydrogen bomb!

The initiative in declassifying the CNF work belonged to the USSR. During the official visit of the Soviet leaders N S Khrushchev and N A Bulganin to Great Britain in 1956, one of the members of the delegation was I V Kurchatov who delivered a lecture at the British Nuclear Research Center at Harwell on the CNF research in the USSR. This was a sensation. British scientists were not ready to discuss I V Kurchatov's proposals to conduct joint research, evidently for the lack of permission from their government.

However, John Cockroft, the leader of the British nuclear research at the time, was so fascinated by the CNF work at Kurchatov Institute (LIPAN) and by the readiness of the Soviet physicists to share the results of research and to collaborate in it that he was able to persuade the British government to declassify nuclear fusion research in Great Britain too. This was the first push to declassifying the data [13, 14, 16].

At the moment, CNF research is being carried out in various countries in many a one directions, having become an arena of comprehensive international cooperation. Appreciable results can be quoted. For instance, the following record characteristics of thermonuclear plasma were obtained in 1997 on the largest tokamak, JET (Joint European Torus), in Culham, UK, whose major radius is $R = 3$ m: thermonuclear plasma temperature $T = 300$ million degrees, energy confinement lifetime is 1.2 s, and fusion power $P_{\text{fus}} = 16$ MW; the ratio of the output power to the externally input energy is $Q = 0.65$, i.e. we are gradually approaching a positive energy balance threshold.

The international experimental magnetic thermonuclear reactor project based on the tokamak, first designed in the

USSR, was initiated by Ronald Reagan and M S Gorbachev; it was to have the following main parameters of the reactor (ITER): major radius $R = 8.1$ m, minor radius $a = 2.8$ m, energy confinement lifetime $\tau_E = 6$ s, fusion power $P_{fus} = 1.5$ GW. This is already a very high power [15]!

But what was the real story of CNF research? The actual circumstances were such that, reflecting the historical unpredictability, the work on investigating the light ion fusion reactions was inevitably tied to the development of atomic and hydrogen bombs. The main cause of this was the Second World War followed by the 'cold war' and the grandiose self-imposed armament race. The creation of high-power nuclear weapons was the main driving factor in the atomic problem.

It was discovered in the process that the power density in an atomic bomb as a result of the fast chain fission reactions proceeded in the active zone is such that temperatures of hundreds of millions of degrees are achieved as in a stellar core, and this is sufficient to trigger the thermonuclear fuel burning. It was thus realized that the atomic bomb could be used as a detonator — a match to fire up the thermonuclear fuel of the hydrogen bomb (heavy isotopes of hydrogen). The efforts were therefore mostly focused on the progress of this direction of research.

Notice, however, that the fusion reaction involving the heavy isotope of hydrogen (D) was discovered in 1934, before the uranium fission reaction (1939). The research and development of controlled-fusion-based thermonuclear power engineering could in theory proceed independently of the work covering fission processes. If the fission reactions were not yet discovered or if they did not exist in nature at all, the nuclear fusion energetics could evolve successfully by themselves, following their own scenario.

The precursor to the study of nuclear fusion reactions of light elements and to the possible beginning of research on CNF could be found in the discovery by E Rutherford, M Oliphant and P Harteck in 1934 of the elementary nuclear fusion reaction in which two D atoms of heavy hydrogen merged into a helium atom and thereby released a huge amount of energy. These authors accelerated deuterium ions in a particle accelerator and then sent them into a target that also contained deuterium atoms.

Then Hans Bethe published his famous article "Energy production in Stars" in 1939 in *Physical Review* [17]. The paper gave some calculated results on thermonuclear reactions deep within stars. The calculations indicated that in order to achieve an appreciable fusion rate in, for example, deuterium plasma, the latter must be heated to a temperature on the order of a billion degrees.

The problem then was to find a technologically feasible method of plasma heating to such temperatures and to thermally insulate it from the reactor wall. A tiny bit was left undone: to formulate the fundamental idea of controlled nuclear fusion — to outline how to apply electromagnetic energy and the electromagnetic field in order to heat deuterium plasma to about a billion degrees and at the same time thermally insulate it from the reactor walls over the time required for the fusion reaction to proceed in terrestrial conditions.

More than ten years passed but, as far as we know, such suggestions were not made; it cannot be excluded, therefore, that the problem was first formulated in the USSR and a constructive solution was only suggested at the beginning of 1950 by the junior sergeant O A Lavrent'ev. He was then 20 years old and found himself on the practically 'uninhabited' island of Sakhalin. After this, events followed one another at a much faster rate.

4. On the first part of O A Lavrent'ev's proposal for the hydrogen bomb design

I have mentioned already that the classified paper by O A Lavrent'ev forwarded to I D Serbin from Sakhalin Island contained two ideas. The second of them (CNF) was characterized above. The first idea was an extension of a physical principle of the design of the hydrogen bomb (H-bomb).

I wish to point out that while O A Lavrent'ev's proposals on CNF were pioneering ideas even as far as the formulation of problem goes, the situation with the hydrogen bomb was different: although by 1950 the design of the hydrogen bombs were not yet completed and the bomb was not yet tested, secret work on it was being carried out in large top-secret research teams both in the USA and the USSR.

It would seem strange at first glance that the first part of O A Lavrent'ev's proposal had for some reason never been discussed before.

I was involved in this sort of work on bomb ever since February 1952, when I arrived in Sarov at the Theoretical Department of the All-Union Research Institute of Experimental Physics (VNIIÉF) after I graduated from the Physics Department of Moscow State University; almost never were there palls of secrecy in our team. It was not infrequent that I needed to write a referee report on the designs of nuclear charges that were sent in from various inventors in the world outside our Institute; nevertheless, neither myself nor my colleagues among researchers ever came across O A Lavrent'ev's name.

Nowadays, having mulled it over, I can only hypothesize that this topic was closed shut even before 1952 as if there was no demand for it, and later it never surfaced again; the relevant documents may exist somewhere in archives or may have been destroyed as obsolete. Certain phrases that indirectly confirm these hypotheses can be found in Lavrent'ev's preprint [8, p. 19].

Even despite this, the principal designs of H-bombs that were offered by various authors in the 1950s may still be of a certain historical interest. This is why I will allow myself to characterize the principal designs of hydrogen bombs given in work [8], assuming as very likely that similar designs were already known to the official designers of the atomic and hydrogen bombs in the USSR and were quantitatively verified in sufficient detail, using the extensive data available on atomic and fusion reactions and their cross sections, including the intelligence information obtained in secret-service work.

Note that from the standpoint of 2001, the hydrogen bomb designs at the level of 1950 are not secret anymore; a lot of materials has been published, including very detailed descriptions of the devices themselves [6, 7].

As we understand now, these designs cannot even be regarded as sufficiently refined. Science, engineering and especially a number of subtle nuclear technologies have greatly progressed since that time.

These proposals must be treated as principal schemes that contained certain physical ideas at the level of 1950, and no more.

It is definitely interesting to know, from the point of view of evolution of science and technology, who suggested what in the 1950s, independently of others, and who invented what at the time when neither the USSR nor the USA had hydrogen bombs and everything was top secret.

The design of the hydrogen bomb as suggested in O A Lavrent'ev's proposal (for the full text of O A Lavrent'ev's proposal of July 29, 1950 see below the Section "From the Archive of the President, Russian Federation", p. 859) is a spherical shell enclosing ^{6}LiD as the thermonuclear fuel for fusion reactions and containing an atomic bomb at the center, thus utilizing the principle of explosion-driven head-on collision of two subcritical hemispheres of ^{235}U or ^{239}Pu. The atomic bomb is a detonator and serves to trigger the thermonuclear fuel burning [8].

It should be said that this is a very reasonable scheme for an initial analysis.

It will be interesting to compare this scheme with those (now available in the open press) that were discussed by A D Sakharov and V L Ginzburg in 1948 and 1949.

I will quote G A Goncharov [1] whose article presents data from declassified archive materials on the Soviet atomic project: "*Turning in his report*[9] *on systems which could be of practical importance, V L Ginzburg made evaluations of the efficiency of a design which consisted of an atomic bomb surrounded with a deuterium layer enclosed in a shell. He pointed to the possibility of successful replacement of the liquid deuterium in this system by heavy water and also made an important remark:* "*We can also discuss 'the burning out' of mixtures that contain lithium-6* (*in order to use the heat produced by the reaction* $^6\mathrm{Li} + \mathrm{n} = \mathrm{T} + {}^4\mathrm{He} + 4.8$ MeV)*, uranium-235, plutonium-239 and so on." This led V L Ginzburg to the idea of using lithium-6 deuteride as a thermonuclear fuel.*"

To be fair, we need to emphasize that V L Ginzburg suggested using the solid (briquetted) chemical compound ^{6}LiD as thermonuclear fuel in March 1949, while O A Lavrent'ev suggested it in July 1950. This establishes the priorities. For obvious reasons, we can also state that the two authors arrived at this idea independently. The Americans came upon using ^{6}LiD instead of liquid deuterium much later.

As we read in paper [1], in June 1951 Edward Teller and Frederic de Hoffmann published a report devoted to the efficiency of using lithium-6 deuteride in the new 'superbomb' design. Americans used the solid chemical compound ^{6}LiD for the first time in the 'Bravo' test on March 1, 1954. However, liquid deuterium was the main fuel for nuclear fusion as late as at the time of the 'Mike' test on the Eniwetok island on November 1, 1952. The explosive device there was not transportable, its weight was around 80 tonnes and it had the TNT equivalent of 10 million tonnes.

As for the proposed design of the 'implosion' type of hydrogen bomb with lithium-6 deuteride at the center of the sphere, given by O A Lavrent'ev in his preprint [8, p.18], the following can be said. It seems to be classified as an 'atomic bomb with fusion-assisted enhancement'.

The diagram given in paper [8] is definitely insufficient for evaluating its importance at that period (1950).

The point is that the diagram there lacks many details that determine to a great extend whether this principle is feasible and efficient. The diagram lacks dimensions, masses, radii; the sequence of physical nuclear processes that set in as a result of implosion of the explosive are not given either. Obviously, the mode of operation of such a system may differ greatly depending on the initial parameters of the system.

I should mention that from the standpoint of today's technology that gave us very fast computers and efficient computation codes, the efficiency of such simple systems can be determined within several minutes [while in the past this would take several months of manual work by a large team of mathematics (laboratory assistants)]. Now we could very rapidly optimize this system on a computer, having varied numerous parameters: dimensions, masses, the arrangement of spherical shells, the addition of other structural elements, and so on.

Notice that the physical ideas inherent in the principal physical designs [8] are currently used also in various ammunition found in nuclear arsenals. In reality, depending on the specific weapons requirements of different branches of the military, the internal and external additional elements may vary, and the sequence of physical processes that occur when a hydrogen bomb explodes may also be quite different. The authors of bomb designs then have to come up with additional subtleties, tricks, scientific intuition and inventiveness. Sometimes these lead to outstanding results!

All this means that the degree of novelty and the importance of hydrogen bomb designs of the 1950s can be evaluated only after a specific and detailed analysis of the original documents.

As I mentioned above, if we look at this from our place in 2001, the physical designs of hydrogen bombs given by O A Lavrent'ev in 1950 can be described as rather primitive. Let us emphasize, however, that O A Lavrent'ev succeeded in his Sakhalin Island schemes of 1950 to point out a number of promising physical ideas, independently of other authors and with considerable insight.

This is true first of all with regard to using the solid chemical compound (briquetted) lithium-6 deuteride (^{6}LiD) as the main fuel for hydrogen bombs, even though the priority in this aspect belongs to V L Ginzburg. By the way, O A Lavrent'ev referred in his proposal of this bomb not to a hydrogen bomb but to a lithium – hydrogen bomb, which seems to be a more suitable description of this design.

It is, of course, impossible that a single human being stranded on Sakhalin Island could know the multitude of possible fusion reactions involving isotopes of lithium and hydrogen and the dependence of their cross sections on temperature! At that moment only selected and not the most important reactions had been known from open press.

The experimental data on specific thermonuclear reactions and their cross sections as functions of temperature (energy) could be generated only by large research teams of physicists, using very costly experimental physical facilities. And all this was then highly classified. This situation must be taken into account when we evaluate both the first and the second ideas in O A Lavrent'ev's proposal of 1950.

It is extremely impressive, of course, that these principal CNF and hydrogen bomb designs and the lithium-6 deuteride proposal for the main thermonuclear fuel were made by a young man who at that time was stranded on a practically 'uninhabited' island.

5. Conclusions

This article is an attempt to use certain open publications and archive materials to analyze a number of events in their chronological sequence and to relate them to the origins of

[9] The report is dated December 2, 1948.

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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