Physics – Uspekhi **51** (9) 911 – 954 (2008) © 2008 Uspekhi Fizicheskikh Nauk, Russian Academy of Sciences

FROM THE HISTORY OF PHYSICS

PACS numbers: **01.65.** + g, **28.41.** – i, **28.70.** + y

L D Landau in the Soviet Atomic Project: a documentary study

G V Kiselev

DOI: 10.1070/PU2008v051n09ABEH006623

Contents

Abstract. **The article presents information about the participation of Academician L D Landau in the Soviet Atomic Project and is based on a study of archive documents of the First Main Directorate. Their analysis points to L D Landau's important contribution to the development of the theory of heterogeneous nuclear reactors and to the computational justification of the first designs of atomic and hydrogen bombs. Many of the quoted documents have never been published before.**

1. Introduction

The Atomic Project in the former USSR involved a considerable number of outstanding scientists, among whom we find I V Kurchatov, Yu B Khariton, V G Khlopin, Ya B Zel'dovich, A D Sakharov, A A Bochvar, and some others, including Nobel Prize winners V L Ginzburg, L V Kantorovich, P L Kapitza, L D Landau, I E Tamm, and I M Frank. The research activities of the Nobel Prize winners in the Soviet Atomic Project have been described earlier with varying degrees of detail. A number of texts dealing with their work between 1945 and 1953 can be found in collections of archived documents of the Soviet Atomic Project published in 2006 – 2007 and prepared for publication in 2008; these are referred to or quoted in the present article. This work was partially done by Yu B Khariton, Ya B Zel'dovich, and K I Shchelkin; some of the documents they prepared are quoted in this article. The author made an attempt to study and systematize the available archived documents of the former First Main Directorate (FMD or PGU in *Russ. abbr.*) of the USSR Council of Ministers, currently the State Corporation Rosatom, that deal with the research activities in the Soviet Atomic Project of the outstanding 20th century scientist, Academician Landau. In view of the 1968 Nuclear Weapons Non-Proliferation Treaty, it is impossible to produce now any complete review of the results of his research on the atomic and hydrogen bombs, although this would be of extreme interest. In order to present some of the documents in a systematic manner, certain documents reproduced in part in earlier publications on the present subject by *Physics – Uspekhi* are quoted again.

G V Kiselev Russian Federation State Scientific Center 'A I Alikhanov Institute for Theoretical and Experimental Physics', ul. B. Cheremushkinskaya 25, 119218 Moscow, Russian Federation
Tel./Fax (7-495) 127 05 43. E-mail: kiselev@itep.ru

Received 31 March 2008
Uspekhi Fizicheskikh Nauk **178** (9) 947 – 990 (2008)
DOI: 10.3367/UFNr.0178.200809d.0947
Translated by V I Kisin; edited by A Radzig

2. Chronology of significant events in Landau's life

The Rosatom archives contain personal files of many leading scientists who took part in the Soviet Atomic Project. Among them there is a priceless document — the questionnaire with Landau's autobiography (copy of 28 October 1946) [1]. An obvious question now arises: why has Landau's personal file

Table 1.

No.	Title of subdivision	Job position (assigned, transferred)	Date of appointment	Salary, rank	Order No., date	Comment
1.	Scientific sector	Head of sector			Order No. 9 of 1 January 1946	
2.	same	Head of sector			Order No. 84 of 1 April 1946	
3.	same	Head of theoretical sector (pluralistically)			Order No. 66 of 1 April 1949	

been kept since 1946 in the PGU archives and in the present archive? The answer to this question lies in the fact that Landau, unaware of the fact, belonged to the 'nomenklatura' (i.e., to a group of persons occupying privileged positions — *Ed. note*). Additional evidence is the ''List of science supervisors of atomic organizations and enterprises and principal directions of research efforts'' signed by A P Zavenyagin and V S Emel'yanov on 25 March 1951 as an appendix to the PGU report ''On progress in the work on development of the atomic industry'' [2]. This list contained Landau's name as ''science supervisor of theoretical and computational work on hydrogen bomb RDS-6t.'' At the same time, we find a significant entry in the ''List of appointments, rewards, transferences and punishments'': ''Not included in the nomenklatura of 1954'' [1]. It is quite clear why this entry appeared there: Landau stopped working on atomic weapons problems in 1954.

Landau's personnel file was kept in the PGU archive because the staff department of the Directorate followed the careers of all important scientists and had requested copies of questionnaires of these people from each organization. This is how a copy of a questionnaire was sent in from Laboratory No. 3 at the beginning of 1946, a month after the laboratory had been established, in which Landau headed the theoretical sector pluralistically. The rule was to keep questionnaires of specialists at the PGU archive for unlimited duration, so now we have a chance to learn Landau's biographical information gathered 60 years ago. The reader can find the recent, official version of the biography of Academician Landau in a book *Heroes of the Atomic Project* [3]. Although the main stages of his life are well known from earlier publications, we begin with a reproduction of the primary copy of his autobiography of 28 January 1946, making an Appendix to his questionnaire [1]:

''Born in Baku in 1908. In 1922 graduated from high school and enrolled at the phys.-math. department of Baku State University. In 1924 transferred to Leningrad State University and graduated from there in 1927. Became a postgraduate student at Leningrad Phys. Tech. Institute in 1926. From 1929 till 1931 was on a science trip abroad for a year and a half. From 1931 till 1932: research worker at Leningrad Phys. Tech. Institute. From 1932 till 1937: head of Theoretical Department of the Ukrainian Phys. Tech. Institute in Khar'kov. From 1937: head of Theoretical Department at the USSR AS Institute for Physical Problems in Moscow. 1937 – 39 was under arrest by NKVD and released as case was closed. In 1943 received the Badge of Honor. In 1945 received the Order of the Red Banner of Labor. In 1945 was awarded the Stalin Prize.''

Author's note: *in fact, he was awarded the Stalin Prize in 1946*.

The ''List of appointments, rewards, transferences and punishments'', filed with the questionnaire but unsigned, only provides partial information on Landau's work at Laboratory No. 3. This list gives the history of Landau's promotions, although not at Laboratory No. 3 but at the Thermo-Technical Laboratory. This means that the above list could be filled and filed with the questionnaire after Laboratory No. 3 got the new name Thermo-Technical Laboratory in 1958 through the USSR Academy of Sciences Resolution No. 229 of April 3. The information from Landau's ''List of appointments, rewards, transferences and punishments'' is given in Table 1.

Two aspects attract attention in this records. First, we see that Landau was one of the first to be appointed to the staff of Laboratory No. 3; this took place on 1 January 1946, a month after the Laboratory was formed on 1 December 1945. This means that the first director of Laboratory No. 3, A I Alikhanov, understood very well the importance of having first-class physics theoreticians on the staff of the laboratory. The invitation for Landau to accept as a pluralist the position at Laboratory No. 3 was a huge plus both for the laboratory and for reactor theoretical physics. The second aspect is that presumably through a slip by a staff department worker, the part-time job was written as starting only on 1 April 1949, while in reality Landau was at the same time the head of the theoretical department at the Institute for Physical Problems from the very start of his work at Laboratory No. 3 on 1 January 1946.

A copy of the questionnaire (the questions are not reproduced in full) is presented in Table 2. On the whole, the questionnaire comprised 39 questions of which items 32 – 39 were queries about the nearest kin. On line 39c Landau wrote: ''Father was arrested in 1930 – 1932.''

Landau's modus operandi in Laboratory No. 3 as head of the theoretical sector (pluralistically) was opposed by General N A Osetrov, authorized by the USSR Council of Ministers to oversee the management of Laboratory No. 3. Osetrov sent L P Beria a ''Memorandum proposing to dismiss L D Landau from the staff of Laboratory No. 3'' with the following argumentation [4]:

''10 March 1949. *Top Secret*

Memorandum

Academician Landau L D occupies the position of head of sector at Laboratory No. 3 as of May 1946.

Landau L D does not hold security clearance from department 'K' of the USSR Ministry of State Security (MSS or MGB SSSR in *Russ. abbr.*) for the work at Laboratory No. 3.

Academician Landau failed to visit Laboratory No. 3 the entire time he was on staff there, except for only occasional visits. For example, Landau did not come to the laboratory even once between May 1948 and 1 February 1949 and visited

Table 2. Questionnaire.

No.	Questions	Answers
1.	About yourself: surname, first name, patronymic	Landau Lev Davidovich
2.	Year, month, day of birth	22.1.1908
3.	Place of birth...	Town of Baku
4.	Ethnic group, mother tongue	Jewish, Russian language
5.	If you ever had other nationality or citizenship, indicate which...	no
6.	Social origin. Social position.	Father: engineer. Employee
7.	Are you a member of, or candidate to become a member of, the Communist Party... ?	no
8.	Have you ever been a member of the CP or another communist party... ?	no
9.	What CP member knows you well and where is he now?	no answer
10.	Member of The Young Communist League (VLKSM)?	no
11.	Past Membership in The Young Communist League (VLKSM)?	no
12.	Have you ever had YCL or CP reprimands... ?	no
13.	Have you ever deviated from implementing the party line, or participated in oppositions and antiparty groups; when, where, in which... ?	no
14.	Have you ever been a member of other parties; which ones, since when and until what date; where?	no
15.	Education. How many classes (courses) of what establishment you had, when and from where graduated: a) school providing general education b) special c) party d) military main specialty scientific degree	 no answer Physics Dept., Leningrad State University in 1927 no no Physicist Academician of AS USSR
16.	Do you have any scientific publications... ?	many
17.	Do you speak, write, etc. a language of another USSR people in addition to your mother tongue, or a foreign language and how well... ?	English, German, French — decently
18.	If you were ever tried in court or under investigation, indicate when, where, by whom and for what...	Arrested by NKVD in 1938, released as case was closed
19.	Have you ever been abroad? When, where, on what assignment. How long were you abroad, why did you leave, why did you return?	Scientific assignment for a year and a half in 1929 – 1931 /Germany, England, Denmark, Switzerland/. To a conference in Copenhagen in 1933 and 1934
20.	Do you have relatives abroad... ?	no
21.	Have you ever served in the Red Army... ?	no
22.	Did you ever live on the territory occupied by the whites... ?	In Baku in childhood
23.	Have you ever served in white or foreign armies... ?	no
24.	Did you serve in old Russian army... ?	no
25.	Have you ever been a POW... ?	no
26.	Do you hold any awards; which, for what? Received them from ... (refer to document): a) in Red Army b) in civil organizations	 no Orders of the Red Banner of Labor and the Badge of Honor Stalin Prize
27.	Membership in labor union, from what date, number of card	Higher Education and Scientific Institutes since 1927
28.	Family situation (number of marriages)	Married for the first time
29.	Do you have children... ?	Son Igor Landau, born in 1946
30.	*Author's note*: *no question on the form*	
31.	Your chosen or party or social work, in parallel with main job, since 1917 until the day you filled in this form (briefly)	Not answered

the Laboratory once or twice in February 1949 for a short time, while the salary he is given of 6000 rubles a month is regularly delivered to his apartment.

Academician Alikhanov A I requested permission to continue having Academician Landau L D in the position of head of sector of Laboratory No. 3 because Academician Landau allegedly advises individual scientists.

Taking into account that Academician Landau L D has no security clearance from department 'K' of MGB SSSR and we do not know whom he advises and what his consulting is, it would be sensible to drop Academician Landau L D from the staff of Laboratory No. 3, and should the need for his consultations arise, oblige Academician Alikhanov A I to request permission from the First Main Directorate in each individual case."

The letter of N A Osetrov raises puzzling questions both in form and in essence. First, it indicates that Landau started working at Laboratory No. 3 in May 1946. However, his questionnaire refers to Order No. 9 of 1 January 1946 with the official appointment of Landau to the staff of Laboratory No. 3. Secondly, it sounds rather strange that Landau had no security clearance for secret jobs. Reference to KGB Department 'K' is also incomprehensible. We know that on 20 March 1943 I V Kurchatov wrote a memorandum to M G Pervukhin on the need to involve L D Landau and P L Kapitza in the work on the atomic issues, in which he pointed out [5]:

"I. At the initial phases of the explosion of a uranium bomb, the predominant part of the material which has not yet taken part in the reaction will be in a very special state of nearly complete ionization of all atoms. The subsequent development of the process and the destructive power of the bomb will depend on this state of matter.

Nothing resembling this state of matter was ever examined experimentally even on the smallest scale, and cannot be observed before the bomb is created. This state of matter is expected to exist only within stars. It is assumed that the general features of the explosion at this stage can be analyzed theoretically. This difficult task could be entrusted to Prof[essor] L D Landau, well-known theoretical physicist, specialist and connoisseur in problems of this sort.

II. When making decisions on choosing the main approaches to solving the problem of isotope separation and designing the appropriate machinery, Laboratory No. 2 needs the consultations and assistance of an outstanding scientist with profound knowledge of physics, experience in experimental work on separation of gases, and an engineer's talent. The scientist combining all these qualities is Academician P L Kapitza.

I am requesting that You consider the proposal of involving Acad[emician] P L Kapitza as a consultant on isotope separation and of entrusting Prof[essor] Landau with the work on calculating the development of the explosion process in the uranium bomb.

Prof[essor] I Kurchatov 20.03.1943."

It appears that I V Kurchatov did not succeed in getting a positive decision and therefore on 24 November 1944 he resumed his attempts, this time addressing L P Beria in a letter "concerning scientists whose participation is necessary for the work on the problem"; an extract about Landau is reproduced below [6]:

"Professor L D Landau

Professor, DSc in physics and mathematics L D Landau, head of theoretical department of the Institute for Physical Problems of the USSR Academy of Sciences — is one of the most profound, talented and knowledgeable theoretical physicists in the Soviet Union.

I raised the question about enlisting him in our work when reporting to C[omra]de V M Molotov. His participation in the work on the uranium problem would be extremely useful for solving profound physical problems involved in the basic processes unfolding in the uranium atom."

We also know of another, later letter, of 18 December 1945 from I V Kurchatov to L P Beria on involving Landau in the work of Laboratory No. 2 [7]:

"To Comrade Beria L P

A number of tasks carried out by the Laboratory and especially those that relate to the industrial product could advance considerably more successfully if Professor, DSc in physics and mathematics Lev Davydovich Landau, head of the theoretical department at the Institute for Physical Problems of the USSR Academy of Sciences, took part in the work.

Prof. L D Landau is the most outstanding theoretical physicist in our country.

I appeal to You with a request to give Laboratory No. 2 permission to involve Prof. L D Landau in the theoretical development of the problems mentioned above and in the sessions of the laboratory seminar.

Head of the USSR Academy of Sciences Lab. No. 2 Academician I Kurchatov."

Note on the document: *underlined by L P Beria.*

The final decision on Landau's participation in the Atomic Project was made on 11 February 1946 during a session of the Technical Council of the Special Committee, which was chaired by the vice-chairman of the Council I V Kurchatov and which took the following decisions [8]:

"II. On samples of the industrial product (reporter Cde. Khariton Yu B)

1. Take the report into consideration.

2. Charge a group of theoretical physicists under the general leadership of Prof. Landau L D to prepare all the materials necessary for quantitative computations relating to tests of samples of the industrial product.

Consider it necessary to organize a computations group equipped with modern computational devices in order to carry out numerical calculations needed to process the materials of the theoretical group."

Author's note: *industrial or plant product was the code word for* '*atomic bomb*'.

We thus see from the documents quoted above that I V Kurchatov's persistent efforts made it possible to enlist Landau in the theoretical work needed for developing the first Soviet atomic bomb (A-bomb). And this means that Landau received the appropriate clearance for A-bomb research which had maximum secrecy level. General N A Osetrov's statement on Landau's lack of clearance is therefore very strange. At the same time, we need to pay attention to the clearance-related note written (in purple ink, not signed) into Landau's personnel form: "To Design Bureau-11 No... of 1.03.50, rejected to others." *Author's note*: *the clearance number is not given here*. We are not aware of any additional materials found in the Rosatom Archive explaining how the above letter of N A Osetrov could appear. It is a matter of speculation, therefore, who was the true initiator of the entire spectacle.

It is probable that General Osetrov discussed with the Director of Laboratory No. 3 Alikhanov the issue of Landau's involvement and of preparing a letter to Beria. Consequently, A I Alikhanov sent Beria a day earlier, on 9 March 1949, a letter on the need to have L D Landau's participation in the theoretical and computational work of Laboratory No. 3 on industrial-scale heavy-water reactor No. 7. We therefore reproduce A I Alikhanov's letter in full [9]:

"Dear Lavrentii Pavlovich!

The authorized person of the Council of Ministers, Cde. Osetrov N A, currently insists on dismissing Acad. L D Landau from the work at Laboratory No. 3. This puts me in such a difficult situation that I cannot help addressing you directly.

The snag is that our knowledge of the specific features of the functioning of facility No. 7 type reactors are based, before we complete the outlined program of measurements on facility No. 7 and their theoretical treatment, on fragmentary and often unreliable experimental data and theoretical evaluations. The parameters of facility No. 7 are inevitably very different from those of the projected industrial-scale unit. Consequently, measurements on the pilot facility cannot be immediately used to adjust the parameters of the industrial-scale system and need a painstaking theoretical processing. This high-responsibility task is being carried out and should be carried out by the theoretical and computations departments of the laboratory in a short space of time. It is especially important when doing it not to overestimate the accuracy of theoretical predictions and of calculations made on the basis of the theory, and thus to avoid unpleasant surprises when the system is launched.

For two years Acad. L D Landau participated in all theoretical projects dealing with the reactor of the type that is of interest to us now. He established that the theory of neutron moderation can be generalized to the moderator we use and determined the accuracy limitations for this theory. Then he outlined the main contours of the theory of a lattice of operating blocks, which was later developed, as applied to the system designed, under his guidance by Pomeranchuk and Galanin. At the present stage his role in critically analyzing individual mathematical methods developed in the theoretical department for calculations on unit No. 7 is especially important to us. The exceptional ability of Acad. L D Landau to rapidly expose weak points of any calculation and to analyze its accuracy boundaries, to find more stringent and more accurate methods of calculations, offers us a chance of having higher confidence in our solutions to the practical aspects of the design.

In order to complete first-priority tasks set for the laboratory, namely, to design unit No. 7 and to process the experimental results gathered on the experimental setup, it would be extremely important not to interrupt the participation of Acad. Landau in the work of the theoretical department in the near future, perhaps at the price of restricting the range of problems supervised by him to the general theory of reactors and to various aspects of the theoretical analysis of results generated by the experimental setup.

This is a request that You issue instructions on the possibility of resolving this problem. In the meantime, I assure You that were it not for the exceptionally serious light in which I regard the participation of Acad. Landau in the theoretical and computational program in these areas, I would never dare write this letter."

The letter bears L P Beria's resolution of 30 March 1949 on a separate sheet, typewritten: "*For Cdes. Pervukhin M G* (*convocation*), *Zavenyagin A P, Meshik P Ya. Please consider Acad. A I Alikhanov's request concerning further work of Acad. Landau at Laboratory No. 3 and make a decision.*"

In view of this instruction, Deputy Heads of PGU M G Pervukhin and P Ya Meshik sent L P Beria a letter stating this [10]:

"Following the assignment received from You, we considered the request from Acad. Alikhanov A I concerning Acad. Landau L D's further work at Laboratory No. 3.

As there is no other group of theoreticians that could without delay continue the work conducted in Laboratory No. 3, and also taking into account that Acad. Landau L D was introduced to the work of Laboratory No. 3, we consider it advisable to grant the request of Cde. Alikhanov A I."

L P Beria honored A I Alikhanov's request and Landau continued to work until the end of 1953 as head of the theoretical sector (pluralistically) in Laboratory No. 3.

A similar confrontation took place in 1949. G A Goncharov recalls in paper [11]: "In view of the decision to intensify the security control over the Soviet Atomic Project, B L Vannikov, Head of the First Main Directorate, and his deputy P Ya Meshik prepared proposals for the meeting of the Special Committee on 18 April 1949 [2, p. 360] which contained the following item: as Academician Landau and a number of physics theoreticians working under his guidance are not politically reliable, we think that it would be advisable to establish in Laboratory No. 2 a group of physics theoreticians consisting of reliable persons (Cdes. Sobolev, Blokhintsev, Sakharov) and charge this group with theoretical work so that Landau's group could be completely replaced and dismissed from working on the problem..." Goncharov points out later that this "proposal has not been implemented." With what we know about B L Vannikov's biography, this initiative could only have started with P Ya Meshik, L P Beria's henchman, responsible in the FMD for personnel and security. This initiative of P Ya Meshik is not really surprising (we have no doubt that he initiated this, of his own volition or on someone else's order) as state security operatives kept constant watch over Landau (as evidenced by the "KGB memorandum concerning Academician L D Landau" [12]).

Landau's questionnaire given above lacks the important information on his election to full membership of the USSR Academy of Sciences on 30 November 1946 or on his decorations. V L Ginzburg made an interesting remark about this election in his book [13]. In footnote 7 to his article about Landau he wrote: "On L D Landau's special tasks. At the first stage I knew nothing about it, and in fact was never curious about it. After the first explosion (that is, on 29 August 1949) L D Landau was on the list of people who received the Order of Lenin. I am therefore quite positive now that Landau was elected USSR Academy of Sciences Full Member on 30 November 1946 as a result of certain actions by I V Kurchatov, who obtained the approval of the Central Committee of the C.P.S.U.." In 1946, Landau was given the rank of Stalin prize laureate for his work "Development of the theory of electron plasma oscillations". A Decree of the Presidium of the USSR Supreme Soviet of 29 October 1949, "On awarding Orders of the USSR to scientific, engineering and technical workers for outstanding achievements in fulfilling a special assignment of the government", decorated Landau with the Order of Lenin [14]. The governmental 'special assignment' stood for the first Soviet atomic bomb and its successful testing at the Semipalatinsk testing grounds. A resolution of the USSR Council of Ministers of 29 October

1949 awarded Landau the Stalin Prize of the Second Class and a bonus of 100 thousand rubles for "developing the theory of evaluation of the atomic bomb efficiency" [15]. As stated in item XXIV of a resolution of the USSR Council of Ministers of 16 May 1950, eleven members of the group of Academician Landau L D, the science supervisor of the work, were nominated by him to receive awards for their participation in computational work for the first atomic bomb, namely A S Kompaneets (15 thousand rubles), E M Lifshitz (15 thousand rubles), N S Meiman (25 thousand rubles), I M Khalatnikov (20 thousand rubles), and some others [16].

On 31 December 1953, Landau was awarded the rank of Stalin prize laureate. The resolution of the USSR Council of Ministers [17] stated:

"The USSR Council of Ministers emphasizes that the creation of the hydrogen bomb and of improved designs of the atomic bomb is a large-scale success of Soviet science and Soviet industries and in this spirit orders: [...]

6. For computational and theoretical work on the RDS-6s and RDS-5 gadgets award the Stalin Prize of the First Class to

1. Landau Lev Davydovich, Academician.

2. Semendyaev Konstantin Adol'fovich, Candidate of Physicomathematical Sciences.

3. Tikhonov Andrei Nikolaevich, Corresponding Member of the USSR Academy of Sciences — in the amount of 100 thousand rubles each."

A Decree of the Presidium of the USSR Supreme Soviet of 4 January 1954 gave L D Landau, together with I E Tamm, A D Sakharov, E I Zababakhin, A N Tikhonov, A P Aleksandrov and some others, the title of a Hero of Socialist Labor "for exceptional services to the state while working on a special assignment of the Government" [18]. Elucidate to the reader that the 'RDS-6s gadget' was the first Soviet hydrogen bomb and 'RDS-5 gadget' was an implosion type atomic bomb of the shell design using a combination of plutonium and uranium-235 nuclear fuel [19].

All these high-status governmental awards are evidence of Landau's sizable contribution to solving the problems involved in designing Soviet atomic and hydrogen weapons.

In conclusion, two unique government-issued documents should be reproduced as they nullify all the above statements on security clearance. Two ministers, V A Malyshev of the Ministry of Medium Machine Building and S N Kruglov of the Ministry of Internal Affairs, on 12 December 1953 sent G M Malenkov at the CPSU (Communist Party of the Soviet Union) Central Committee a memorandum "On bodyguards for the leading scientists and specialists executing task orders of the Ministry of Medium Machine Building"; extracts from this report [20] are given below:

"To Comrade Malenkov G M

In accordance with the assignment of the Presidium of the CPSU Central Committee on setting up protection for the leading scientists and specialists executing task orders of the Ministry of Medium Machine Building, we report the following actions.

At the current moment, the USSR Ministry of Internal Affairs (MVD in *Russ. abbr.*) provides bodyguards to Academicians Kurchatov I V, Kikoin I K, Aleksandrov A P, Artsimovich L A, Alikhanov A I, and Khariton Yu B.

We also consider it necessary to provide protection to Academicians Sakharov A D, Landau L D, and Bochvar A A and to the Director of object 'V' of the Ministry of Medium Machine Building, Professor Blokhintsev D I."

On the basis of this report, the USSR Council of Ministers passed Resolution No. 2959-1273ts on 16 December 1953 in which item 1 stated [21]:

"The USSR Council of Ministers orders:

That the following proposals of Cdes. Malyshev and Kruglov be accepted:

a) assign to the USSR Ministry of Internal Affairs the task of setting up protection for Academicians Sakharov A D, Landau L D, Bochvar A A, and for the Director of object 'V' of the Ministry of Medium Machine Building, Professor Blokhintsev D I."

This document has a footnote indicating that Malyshev and Kruglov's proposals concerning protection of the leading scientists and specialists were considered and approved at the meeting of the Presidium of the CPSU Central Committee (protocol No. P44/18 of 16 December 1953). The documents quoted above point to the high state-level significance of Landau in the Soviet Atomic Project.

We need to mention that after Landau left Laboratory No. 3, the position of head of the theoretical sector was taken on by his student, an outstanding theorist, Academician I Ya Pomeranchuk, who added to his achievements in theoretical nuclear physics a fundamental contribution to applied sciences — he took part independently of American scientists in establishing the theory of heterogeneous nuclear reactor computation (see, e.g., Ref. [22]). After Landau distanced himself from the work on the hydrogen bomb, the work at IPP on atomic and hydrogen weapons development was headed by his student Isaak Markovich Khalatnikov.

3. Specifics of work management of the Atomic Project

To better understand the conditions under which Landau's 'atomic' activities unfolded, we give here brief information on the arrangement of the works on the Soviet Atomic Project. The Atomic Project, whose main goal was the creation of an atomic bomb and subsequently a hydrogen bomb, is a concept that has formed in the last decade in official documents and various publications. It is assumed that the Atomic Project existed during the time of the Special Committee headed by L P Beria and of the First Main Directorate (PGU in *Russ. abbr.*) headed by B L Vannikov from 1945 to 1953, when the Ministry of Medium Machine Building (MSM in *Russ. abbr.*) was established. The decisions of the Special Committee and the PGU, formed for controlling the work on nuclear weapons, were binding for all People's Commissariats (Ministries) of the country. Furthermore, these decisions were supported in most cases by resolutions of the USSR Council of Ministers. From the moment these two powerful state management bodies started operations, they created a routine of collectively discussing managerial and scientific and engineering decisions at their meetings and during the meetings of the scientific and technical councils, combined with strict personal responsibility. The work of the Scientific Council and Engineering and Technical Council of the Special Committee were organized in the same way (they were subsequently merged into the PGU Scientific and Technical Council (NTS in *Russ. abbr.*), which included a number of outstanding Soviet scientists. Later on, the Scientific Council of the President of the USSR Academy of Sciences, S I Vavilov, was set up to coordinate the activities of the academic institutions involved in the atomic issues. The Scientific Council of the Special Committee had 26 meetings before March 1946 when the PGU NTS was organized; the latter council had 112 meetings before 1953. At the first stage, B L Vannikov, Head of the PGU, became chairman of the Scientific Council of the Special Committee and the PGU NTS. Consequently, any decision of scientific councils would be binding for every organization participating in the Atomic Project. Later, I V Kurchatov headed the PGU NTS for a considerable time. Leading scientists and engineers were invited to such meetings of scientific councils to give information or to report on specific issues, or as experts.

It should be remembered that the work on developing the first Soviet atomic bomb was run in an exceptionally closed manner, with extraordinarily strict measures maintaining the highest top secret security environment. The PGU NTS could be attended only by those engaged in given specific work and possessing the appropriate clearance issued by the KGB. Even high-ranking PGU bosses were unable to take part in NTS sessions without permission from B L Vannikov or A P Zavenyagin, and then only if they were working on this problem. One of the measures introduced by security personnel in order to prevent, as they believed, leaks of classified information was to use code words for technical terms and plant designations. Therefore, Landau was obliged to use these code words: facility No. 1 — uranium – graphite reactor; facility No. 2 — heavy-water reactor; jet engine, industrial or plant product, gadget — atomic bomb, etc. It is difficult to say now who invented these code words. Most of the documents prepared personally by Landau or with his participation bore the seal of secrecy assigned for work on the A-bomb: the top secret/special dossier; only specialists who held proper security clearances (in other words, permission from the KGB) had the right to participate in works on development of the atomic bomb and to compose such classified documents. Landau did have such a clearance.

4. Landau and the PGU Scientific and Technical Council

The PGU Scientific and Technical Council started its work in April 1946 after the USSR Council of Ministers Resolution was issued [23]. The members of the NTS were B L Vannikov (chairman), Academician I V Kurchatov (deputy chairman), M G Pervukhin (deputy chairman), Academician A F Ioffe, Academician V G Khlopin, Academician A I Alikhanov, Academician N N Semenov, Corresponding Member of the USSR Academy of Sciences I K Kikoin, Corresponding Member of the USSR Academy of Sciences D V Skobel'tsyn, Professor Yu B Khariton, V A Malyshev, A P Zavenyagin, Professor A I Leipunskii, and B S Pozdnyakov (learned secretary), i.e., ten out of 14 members of the Council were scientists. In 1946, the meetings of the NTS discussed 209 various scientific, technical, and organizational problems. The following areas were covered: development of uranium-graphite and heavy-water reactors, work on diffusion-based, electromagnetic, and centrifugal separation of uranium isotopes, mining and then production of metallic uranium and thorium, the technology for manufacturing plutonium and heavy water, the preparation of the testing grounds, the development of accelerators, nuclear physics research, plant design projects, work plans, and reports of the institutes. In 1946, problems related to the development of atomic bombs were discussed only once (18 December 1946) [8].

L D Landau took part several times in PGU NTS sessions, once presenting a report but mostly as an expert. Here is chronologically arranged information on this side of Landau's activities.

On 22 July 1946, the PGU NTS heard a report by the Director of the Institute of Chemical Physics (ICP) Academician N N Semenov on measures to arrange the testing grounds and conducting the tests [24]. In item 2 of the decision of this NTS session we read:

"2. Charge a commission consisting of Corr. Member of the USSR Academy of Sciences Cde. Tamm I E, Prof. Zel'dovich Ya B, Prof. Landau L D, and Prof. Levich V G to check within ten days the theoretical calculations submitted by the Institute of Chemical Physics of the USSR Academy of Sciences and submit an evaluation of the initial data accepted for conducting the said calculations relating to the propagation of the explosion and of phenomena taking place at its various stages (transfer of the energy of fragments to X-rays, formation and cooling of a gas volume at very high temperature and pressure, formation and propagation of the shock wave, propagation of neutrons, etc.).

Submit the conclusions in writing for the approval of the Scientific and Technical Council."

On 29 August 1946, Landau took part in a PGU NTS meeting which heard "the conclusions of the expert commission of Cdes. Landau L D, Tamm I E, Levich V G, and Zel'dovich Ya B on the theoretical part of the report by Academician Semenov N N, which recognized the newly developed theory of the cooling wave and the theory of the explosion as a whole as correct" [25]. *Author's note*: *conclusion not signed by I E Tamm.*

Landau's first talk at an NTS meeting was a large report "Theoretical studies in nuclear physics" (see below) on 10 February 1947 [26]. Speaking at the meeting were NTS members I V Kurchatov, V A Malyshev, A I Alikhanov, A P Aleksandrov, Yu B Khariton, Ya B Zel'dovich, and M G Pervukhin. Stenographic notes were regularly taken during NTS meetings, but they were unfortunately lost and we shall never know what the speakers had to say. The following decision was taken concerning Landau's report:

"As reported by Landau L D, a number of computational studies were conducted recently in theoretical nuclear physics in relation to the arising practical issues (contents of the report are attached).

Having discussed the report by Landau L D on theoretical studies in nuclear physics, the Scientific and Technical Council resolves:

1. To take Cde. Landau L D's report on theoretical work on nuclear reactions into consideration.

2. Entrust Cdes. Landau L D, Zel'dovich Ya B, Pomeranchuk I Ya, and Tamm I E with elaboration of a plan of theoretical studies in nuclear reactions for the year 1947 and submit it within two weeks' time.

Charge Cdes. Kurchatov I V, Alikhanov A I, and Semenov N N with consideration of the indicated plans of theoretical studies and submission of the aggregate plan for the approval of the Council... ."

In most cases, the PGU top echelon followed normal procedure and on the basis of the results of discussions at the NTS signed special assignments to the heads of organizations mentioned in the decision of the NTS. In this connection, M G Pervukhin signed the following assignment [27]:

"To Aleksandrov A P, Landau L D

NTS Assignment (61-1)

In accordance with the decision of 10.2.1947 I request that You assign to Cde. Landau L D the task of compiling, in collaboration with Cdes. Zel'dovich Ya B, Pomeranchuk I Ya, and Tamm I E in the appropriate segments of the assignment, a plan of theoretical studies in nuclear reactions (indicating the names of the principal executing scientists and job deadlines) and submitting it within two weeks for the approval by the commission of Cde. Kurchatov I V."

Unfortunately, the plan mentioned in this decision of the NTS could not be found in the Rosatom Archive, and it had never been discussed at NTS sessions during 1947.

On 2 June 1947, A P Aleksandrov, Director of the USSR Academy of Sciences Institute for Physical Problems (IPP or IFP in *Russ. abbr*.), and L D Landau delivered to an NTS meeting a "Plan of IPP research for 1947, including work on theoretical computational studies in nuclear physics" [28]. Reading this plan demonstrates that "theoretical computational studies in nuclear physics" involved work on the A-bomb.

On 25 August 1947, a PGU NTS discussed A I Alikhanov's report on the initial outlines of the technical task orders for the industrial-scale heavy-water reactor [29]. The decision of this NTS said:

"1. It is assumed as necessary to conduct an expert checking of theoretical calculations submitted by Laboratory No. 3 and forming the basis for the present preliminary task order.

Charge Cdes. Semenov N N, Kurchatov I V, Leipunskii A I, Zel'dovich Ya B, and Landau L D with preparing a concluding decision on the calculations for the task order on the design of the industrial-scale facility No. 2 submitted from Laboratory No. 3 by Cde. Alikhanov A I.

The expert analysis of the said calculations shall be completed within twenty days and the corresponding conclusion shall be submitted for approval by the NTS."

In view of this decision, B L Vannikov signed the following assignment [30]:

"To Semenov N N, Kurchatov I V, Leipunskii A I

Assignment No. 89

In accordance with the NTS decision of 25.08 of this year I request that You, together with Kurchatov I V, Leipunskii A I, and Cdes. Zel'dovich Ya B and Landau L D, conduct an expert evaluation of the theoretical calculations submitted by Laboratory No. 3."

On 11 December 1947, the USSR Academy of Sciences Institute of Chemical Physics (ICP or IKhF in *Russ. abbr*.) Director Academician N N Semenov informed a meeting of PGU NTS on "The plan of research at the Institute of Chemical Physics" [31]. N N Semenov reported to the council that in accordance with the acting decisions the ICP is conducting:

"a) studies for KB-11 on a computational and theoretical basis for designing the products;

b) a study of promising aspects related to the action and specific features of the products;

[...] ... preliminary calculations were done of the convergent spherical wave and premature triggering of the product."

Author's note: *the work referred to by N N Semenov was carried out in the theoretical sector of the ICP under the leadership of Ya B Zel'dovich before he was transferred to KB-11.*

The explanatory note accompanying the research plans of the theoretical department of the ICP, signed by N N Semenov and head of the theoretical department of the ICP, Corresponding Member of the Academy Ya B Zel'dovich, stated [31]:

"2. The department has developed a detailed theory of neutron multiplication; the resulting theory was applied by us together with Landau's group to calculations of efficiency.

Moreover, this work allowed the department to elaborate the probability theory of premature explosion. These calculations are also of great importance for experiments on determining critical masses and for kinetic experiments at low supercriticality."

The NTS took the following decision concerning the calculations conducted by the ICP:

"4. Entrust Cdes. Landau L D, Sobolev S L, Khariton Yu B, and Kurchatov I V with the checking (expert evaluation) of the theoretical calculations done by the Institute of Chemical Physics on premature triggering of products."

In view of this decision, B L Vannikov signed the following assignment [32]:

"To Semenov N N

Assignment No. 100(s)

[...]

b) Organize the preparation of an expert evaluation (Cde. Landau L D, Cde. Sobolev, Cde. Khariton Yu B, Kurchatov I V) of the calculations relating to premature triggering, which were submitted by the ICP."

In his letter to I V Stalin of 30 June 1947 Academician N N Semenov, ICP Director, formulated an idea of an anti-atomic protection system using neutrons which will be generated in the fissile material of an A-bomb by protons sent from an accelerator located on the ground [33]. N N Semenov offered the following data: "...as follows from very reliable calculations, protons with the energy of 1 billion [electron-]volts can propagate in the air as a directed beam for up to 3 km, and with the energy of 2.7 billion [electron-]volts — for up to 10 km. Having penetrated the body of the bomb, high-energy protons will certainly knock neutrons from nuclei and at sufficient neutron flux intensity will cancel out the possibility of an explosion." This proposal was discussed several times at PGU NTS meetings. This topic holds special interest for today's researchers but here we only present information on Landau's participation in the expert evaluation.

On 13 January 1948, the PGU NTS discussed N N Semenov's proposals concerning the idea of an anti-atomic guard and assigned to the NTS Learned Secretary B S Pozdnyakov, together with Academicians A I Alikhanov and L D Landau, to discuss them and to draft an appropriate conclusion [34].

On 26 January 1948, the PGU NTS passed the following decisions after discussing the above conclusion [35]:

"Item 3. We take into consideration that the commission (Cdes. B S Pozdnyakov, A I Alikhanov, L D Landau) fulfilled the NTS assignment of 13.01.1948 and prepared extensive findings in the matter of N N Semenov's proposal of using accelerators for protection against the action of the products.

Entrust M G Pervukhin, I V Kurchatov, Malyshev V A, Zavenyagin A P, Khariton Yu B, N N Semenov, and Aleksandrov A S with careful consideration of the submitted extensive findings concerning N N Semenov's proposal within three days."

On 29 January 1948, Landau was invited to an NTS meeting for a repeated discussion of the proposal by Academician N N Semenov on "using accelerators for protecting against the action of products [atomic bombs]" [36]. The list of people invited to attend the meeting is of interest. In addition to NTS members (Pervukhin, Kurchatov, Alikhanov, Zavenyagin, Pozdnyakov) also present were PGU deputy head A S Aleksandrov, L D Landau (the only scientist among the invited), authorized person of the Council of Ministers A N Babkin, and I I Sokolov from the staff of the PGU NTS. The NTS passed the following decisions:

"[...] After going through all details of the submitted findings and having heard the comments from Cde. Semenov N N, clarifications by Cdes. A I Alikhanov, L D Landau, and B S Pozdnyakov, and arguments offered by Cdes. I V Kurchatov, Zavenyagin A P, Aleksandrov A S, and Pervukhin M G, the Scientific and Technical Council resolves:

1. To mostly approve the submitted findings concerning Cde. N N Semenov's proposal of 30 June 1947 on using accelerators as means of protection against the action of products."

The final report prepared by B S Pozdnyakov, A I Alikhanov, and L D Landau "On the proposal by Academician Semenov N N (on using accelerators as means of protection against the action of products)" pointed to the following [37]:

"1. On the strength of the assignment of the Scientific and Technical Council of 13 January 1948, the Commission composed of Cde. Pozdnyakov B S, Cde. Alikhanov A I, and Cde. Landau L D went through the available material concerning the proposal by Academician Semenov N N to employ accelerators as means of protection against the action of *products* and prepared the present extensive findings for the Scientific and Technical Council on the problem mentioned above.

2. As initial data characterizing the proposal from Cde. Semenov N N we used the materials (browsed by Cde. Landau L D) listed by Cde. Semenov N N (list attached).

These documents are approximate theoretical calculations carried out at the Institute for determining the required accelerator power, evaluating the effect of interaction with matter and changes caused in the effect of the explosion, and clarifying some other aspects."

We do not reproduce this final report here in full, as it is too large (29 pp.), and as it is possible to get acquainted with its main ideas in the text of the NTS final report [38].

On 5 April 1948, Landau took part in a meeting of PGU NTS at which a project of an industrial-scale heavy-water reactor proposed by the USSR Academy of Sciences Laboratory No. 3 was considered; the meeting discussed the opinion of a commission of experts that consisted of N N Semenov, I V Kurchatov, L D Landau, and Ya B Zel'dovich concerning the design of this reactor [39].

At the beginning of January 1951, I V Kurchatov made a request [40] to B L Vannikov, the PGU head, for authorization to enlist a group of specialists, and L D Landau among them, in work on a fusion reactor. B L Vannikov's reply was received on 20 January 1951, granting permission for the participation of L A Artsimovich, L D Landau, D I Blokhintsev, I Y Pomeranchuk, B I Davydov, A M Andrianov, V A Yavlinskii, S M Osovets, V I Veksler, and S Yu Lukyanov in this project [41].

On 23 July 1951, a representative meeting chaired by I V Kurchatov took place that considered the results and main areas of research at facility 'M' (phasotron) of the affiliate of LIP AN SSSR [the affiliate was subsequently reorganized into the Hydraulic Engineering Laboratory (HEL), then into the Joint Institute for Nuclear Research (JINR)] [42]. Taking part in the meeting were Yu B Khariton, Ya B Zel'dovich, I E Tamm, L D Landau, A D Sakharov, D V Skobel'tsyn, L A Artsimovich, D I Blokhintsev, M G Meshcheryakov, and some others. To quote the protocols of the meeting: "I E Tamm, D V Skobel'tsyn, L D Landau, L A Artsimovich, and A D Sakharov, who presented their comments and suggestions to the meeting, gave high marks to the work carried out at the facility over 18 months and expressed their support for the main areas of research written into the plan for the second half of 1951."

On 5 May 1952, a PGU NTS meeting took place at which it discussed a report by M G Meshcheryakov, Director of the LIP AN SSSR affiliate, on the results of work and the plan of subsequent research at the facility 'M' (phasotron) [43]. D I Blokhintsev, M A Markov, L D Landau, I Ya Pomeranchuk, N A Dobrotin, and V I Veksler presented their inferences from the report.

Landau's conclusion that he presented to the NTS meeting and that we reproduce below in full [43, (to ref. number 1026ts/sd of 24 November 1951)] was of great interest:

"Evaluation of the report on research work carried out at facility 'M'.

The report presents the results of work that lasted approximately a year and a half. The fact to emphasize first of all is the large amount of research completed. The works progressed simultaneously in a number of various directions, with many significant new results of considerable scientific importance achieved in each of them.

1. Studies with artificial mesons

The following results obtained in this field are of special interest.

New particles heavier than the π-meson up to masses on the order of 600 were not observed in any appreciable numbers. This result is especially interesting in view of the fact that the facility 'M' produces the highest-energy accelerated particles.

The cross section of the production of neutral mesons by protons with energies 490 MeV was evaluated. It was found to be greater by a factor of several dozen than that measured earlier at 340 MeV. It would be of great interest to further extend these experiments, both aiming to improve accuracy and assuming a passage from carbon to hydrogen targets.

Investigation of the nuclear interaction of fast negative π-mesons. In this field, the authors extended the study of interaction processes to a not yet investigated range of energies and showed that an effective cross section of nuclear interaction is independent of the π-meson's energy; the authors point to the fact that the π-meson's energy is mostly carried away by neutral particles. This feature has not yet been reported in the current literature.

2. Experiments with high-energy neutrons

We should single out first of all the studies of scattering of 380-MeV neutrons by protons (the maximum energy achieved before was 260 MeV). These experiments showed that scattering is independent of energy in the range from 260 to 880 MeV (in contrast to the range 90 – 260 MeV) and is isotropic in a considerably wide range of angles. Extending this area of research was of great interest to us in the sense of studying scattering of 490-MeV protons by protons and also neutrons by deuterons (which would make it possible to study the scattering of neutrons by neutrons) and of 490-MeV protons by deuterons (which would make it possible to study the scattering of neutrons by protons at still higher energies). Furthermore, a study of protons and neutrons scattering by deuterons would provide additional information on nuclear forces.

The authors conducted systematic measurements of nuclear cross sections for 380-MeV neutrons. Consequently, the previously known results have been extended to an essentially new energy interval. It was found in the process that the effective cross sections become independent of energy.

A detailed investigation of the interaction between fast neutrons and heavy nuclei was conducted. The authors were able to separate the 'vaporized' neutrons from secondary high-energy neutrons. A relation was established between the number of neutrons produced and the mass of the nucleus and the energy of the primary neutrons. In general, it can be said that the authors succeeded in creating a fairly clear picture of the phenomena that take place in collisions of neutrons with nuclei, in contrast to a rather chaotic situation reigning in the literature.

Systematic measurements of fission by fast neutrons were carried out, both for heavy nuclei and for nuclei of mid-range atomic weights.

3. Explorations into nuclear fissions caused by fast particles

A large number of studies relating to collisions between nuclei and fast protons, deuterons, and α particles have been carried out. It should be noted at this point that the authors observed an intriguing phenomenon of the simultaneous ejection of two protons at a small angle to each other.

4. Radiochemical investigations of nuclear reactions occurring at high energies

Deserving special mention is the large volume of experiments conducted and the systematic fashion of running the experiments.

5. Theoretical work

A considerable amount of meson-theoretical calculations were carried out, with the results often obtained before similar work was completed abroad. I wish to specially single out I Ya Pomeranchuk's idea of the possibility of obtaining some results without making concrete assumptions about specific meson interactions.

A B Migdal was the first to point to the role played by a resonance in various two-nucleon processes. This allowed him to clarify essential properties of the spectrum of π-mesons produced in collisions of nucleons.

I Ya Pomeranchuk carried out a detailed analysis of nucleon–deuteron collisions and showed that measurements at small scattering angles can provide valuable information about nuclear forces.

The above list contains only the issues that I consider the most interesting. I have no doubt that this work is an important contribution to nuclear physics and that the Hydraulic Engineering Laboratory of the USSR Academy of Sciences is now a full-fledged research center capable of solving large-scale scientific problems.

Looking now at the direction of further research, I believe that the most important task is to study processes involved in elementary interactions, i.e., the processes involving neutrons and the lightest nuclei — hydrogen and deuterium, such as collisions between π-mesons and protons and deuterons.

Now I would like to add that this field of work facing facility 'M' is so complex that both our most prominent physicists, especially experimenters, should be involved in the work at this facility, and our talented young scientists should mature by using it.

Academician Landau 24.11.51.''

Landau's inference reproduced above is evidence of his keen interest in experimental results obtained at the HEL accelerator and in the important consequences for the theory that he mentioned. The materials documenting the session chaired by I V Kurchatov on 23 July and an NTS meeting of 5 August 1951 are in themselves of great interest to physics historians; it would be advisable to prepare them for publication.

It is thus clear from the above that Landau was closely involved in discussions of various complicated problems as a highly qualified expert. It should be mentioned that the problems stemming from the development of the atomic bomb were only infrequently discussed at the PGU NTS at the initial stage of the Atomic Project, all through 1946. Perhaps this is the reason why I V Kurchatov addressed B L Vannikov, the PGU head, at the end of 1946 proposing this [44]:

''Assuming the need at the present stage of the development of works to speed up progress in the experiment and the theory in the field of reactions with fast neutrons in relation to processes in the 'jet engine', we request Your permission to organize a permanently functioning seminar based on the Institute of Chemical Physics and chaired by Academician N N Semenov, where work in this area conducted by the staff of Laboratories Nos 2 and 3, the Institute of Chemical Physics, and the Institute of Mathematics of the Academy of Sciences would be discussed, with the following members... .'' I V Kurchatov suggested including in the seminar, in addition to specialists from Laboratory No. 2, ICP, IPP, and research fellows from Laboratory No. 3: ''Landau, Pomeranchuk, Alikhanov, Leipunskii A I.''

Author's remark: *A I Leipunskii was for a while on the staff of Laboratory No. 3.*

This letter carried the following resolution by B L Vannikov dated 12 December 1946: ''I do not consider that such a broad-based discussion of the problems of the laboratory would be expedient. Comrades Kurchatov, Pervukhin, and Zavenyagin agreed with this.'' I V Kurchatov, who understood the importance of collegially discussing the 'bomb' problems among specialists and took into account Vannikov's attitude, came up half a year later with a suggestion to organize a special scientific council within Laboratory No. 2. On 19 June 1947, the USSR Council of Ministers made a decision to ''form in Laboratory No. 2 of the USSR Academy of Sciences the Scientific and Technical Council for discussing the science and engineering aspects of developing the RD construction and analyzing the work of individual elements of these constructions''; it was to be chaired by I V Kurchatov and was first given the title ''NTS for problems of KB-11'', later changed to NTS No. 2 [45]. *Author's comment*: *Acronym RD* (*in Russ. abbr.*) *stands for* '*jet engine*' — *code designation of the atomic bomb.* Landau was not included in the initial list of members of this NTS, although by a decision of the PGU NTS was enlisted to work on the atomic bomb issues at the end of 1946. Despite the appearance of the ''NTS for problems of KB-11'', I V Kurchatov was insistent in 'pushing' for the organization of the scientific seminar and was finally successful. Item 8 of the governmental resolution of 10 June 1948 read [46]:

"8. To coordinate the computational and theoretical works and for monitoring the performance on the assignments foreseen by the present Resolution, an access-controlled seminar shall be set up at the USSR Academy of Sciences Laboratory No. 2, consisting of:

1. Academician Landau
2. Academician Petrovskii
3. Academician Sobolev
4. Academician Fock
5. Corresponding Member Zel'dovich
6. Corresponding Member Tamm
7. Corresponding Member Tikhonov
8. Corresponding Member Khariton
9. Professor, DSc Shchelkin.

Entrust Academician Sobolev with the task of chairing the seminar."

It took another eighteen months for governmental Resolution No. 827-303 to induct L D Landau, together with I E Tamm, A D Sakharov, G N Flerov, and some others, into the "NTS for problems of KB-11" on 26 February 1950 [47]. This NTS was mostly convened at KB-11, to which Landau was never invited and thus was a member of this council only formally.

I V Kurchatov knew full well Landau's stature as an outstanding scientist. Consequently, he invited him to his institute to deliver a course of lectures. In this case, Kurchatov wrote the following letter to V A Malyshev [48]:

"To Comrade Malyshev V A

According to an earlier agreement, I am sending herewith the program of the course of lectures on the fundamentals of the theory of atomic nuclei that will be delivered by Academician LANDAU L D.

The lectures will take place at the LIP AN SSSR club once every two weeks on Tuesdays from December 1953 to March 1954.

The lectures are intended for researchers at the LIP AN SSSR working in the field of nuclear physics.

Physicists from other physics institutions will also be invited, namely from the Physics Institute, Institute for Physical Problems, Thermo-Technical Laboratory and Hydraulic Engineering Laboratory, Institute of Chemical Physics, NIFI-2.

The first lecture is to take place on Tuesday 15 December 1953 at 10 a.m.

APPENDIX: As printed (nonclassified) on 1 sheet.

Academician I Kurchatov 2 December 1953

Program of the lecture on the theory of atomic forces

I. Nuclear forces

1. Fundamentals of the general theory of scattering.
2. Classification of nuclear forces.
3. Quadrupole moment of the deuteron.
4. Interactions at low energies.
5. Isotopic invariance.
6. Scattering at high energies.
7. Saturation of nuclear forces.

II. Structure of atomic nuclei

1. Self-consistent field.
2. Scheme of particle coupling.
3. Calculation of magnetic moments.
4. Isotopic nuclear spin.
5. Quadrupole nuclear moments.
6. Periodic system of light nuclei.
7. Magic numbers.
8. Nonspherical nuclei and their specific features.
9. Excited nuclear states.
10. Similar states of isobars.
11. Nuclei with a mass number of 5.
12. Rotational levels of nuclei.

III. Nuclear reactions

1. Intermediate nuclei.
2. Statistical theory of nuclei.
3. Theory of diffraction scattering.
4. A reaction involving deuterons.
5. Nuclear photoeffect.
6. Correlations of protons and neutrons.

IV. Pi mesons

1. General theory of elementary particles.
2. Main characteristics of π mesons.
3. Isotopic spin of π mesons.
4. Decay of the π-zero meson.
5. Meson interactions and the emerging difficulties.
6. Specifics of the production of π mesons.
7. Scattering of π mesons by nucleons.
8. Magnetic moments of nucleons.
9. Multiple production of π mesons."

Signed by I V Kurchatov, mb. 5380.

5. First applied works

We will describe Landau's first scientific paper that had immediate relation to the technology of heavy-water production. We know that at the initial stage of work Laboratory No. 2 was developing heavy-water reactors in parallel with uranium–graphite ones. However, the former needed large amounts of heavy water, which was not manufactured in the USSR. Consequently, the plan drawn up for Laboratory No. 2 for the 2nd half of the year 1943 required developing the technology and equipment, under the guidance of Professor M O Kornfeld, for producing heavy water with a deuterium content of 90–98%, and conducting the appropriate theoretical work. One such project conceived by two researchers of Laboratory No. 2, M O Kornfeld and D M Samoilovich, was devoted to isotope separation by the rectification method. In principle, this method could also separate isotopes of heavy elements (they hoped even uranium isotopes could be separated). Kornfeld and Samoilovich wrote a report, "Separation of isotopes by rectification", in which they first of all calculated the separation coefficient of rectification columns as a function of vapor pressure of the isotopes separated [49]. In the report, its authors wrote: "As we see from theoretical studies by Herzfeld and Teller, vapor pressures of various isotopes are slightly different. Upon our request, Landau extended the results of these authors and arrived at a simple and elegant formula that relates $\Delta P/P$ to isotope mass and the properties of the liquid." Attached to the report is L D Landau's paper "Vapor pressure produced by isotopes" [50].

The authors of the report [49] remark: "Landau's formula implies that the separation coefficient decreases extremely steeply with increasing atomic weight." I V Kurchatov gave this formulation to this conclusion applied to the separation of uranium isotopes: "At the moment, the employment of rectification columns is hampered by the fact that we do not know even one uranium compound that would be liquid at room or lower temperatures" [51]. We can nevertheless infer that Landau directly facilitated the implementation of the rectification method, as applied to liquid hydrogen, with the object of manufacturing heavy water (see, e.g., the letter from PGU to L P Beria of 18 June 1946 and the USSR Council of Ministers Resolution No. 2225-913ts "On building a pilot facility No. 474 at the Gorlovka plant of nitrogen-containing fertilizers of the Ministry of Chemical Industry" using equipment for rectification of liquid hydrogen) [52].

It should be noted that despite Landau's heavy workload and his passion for problems of theoretical physics, he prepared in 1946 a scientific-popular article, "Atomic energy", that hardly anyone remembers now and that is completely unknown to the younger generations [53]. This article is not mentioned either in publications about Landau or in the list of his works that the author was able to scan. It is therefore reproduced in Appendix 2 as evidence of his characteristic trait of teacher and enlightener and at the same time of Landau's unquestionable interest in the problems of the utilization of atomic energy. The story of obtaining permission for its open publication is interesting as one example of the type of communications between the PGU apparatus and scientists at the time; by the way, today's manner of dealing with scientists is no different. A letter from B L Vannikov to the Special Committee secretary V A Makhnev of 17 June 1946 [54] says:

"The article written by L D Landau was reviewed by Professor V G Levich.

Professor Levich V G thinks it expedient to censor the following passages from the article, as their content goes beyond the framework of the official American information (the book by Smyth):

1. Mass of the bomb — p. 146.

2. Remarks on how parts of the bomb are brought together — p. 147.

3. The amount of U-235 in the American bomb — p. 147.

4. Discussion of the possibility of a chain reaction in light elements — pp. 151 – 152.

This abridgement should not significantly change the overall quality of the article and can be done without debasing it in any way."

Compilers' comment added to the document [54]:

"No page proofs of L D Landau's article were found. However, we started a search and were able to establish that the version of the article with a number of passages omitted in compliance with the instructions of the reviewer was published in 1946 as a manuscript by the Committee on the Introduction of Radio and Radio Broadcasting of the USSR Council of Ministers.... After official permission to publish was signed on 12 October 1946, a print run of the article (560 copies) was produced by the printers of the Glavsevmorput' Publishing House (Moscow)."

6. Landau's principally important contribution to the theory of nuclear reactors

After the establishment of Laboratory No. 3 on 1 December 1945 (its first director was Academician A I Alikhanov), the development of heavy-water reactors was moved from Laboratory No. 2 to Laboratory No. 3. Academician A I Alikhanov as a scientific leader of the heavy-water project understood very well the significance and importance of physical calculations for reactors. It is no accident therefore that Alikhanov invited Landau to lead the theoretical sector of the Laboratory; its main task at the initial stage was to develop the theory and methods of calculations relating to heavy-water reactors. Landau started developing the methods of calculation of heterogeneous nuclear reactors in Laboratory No. 3 together with I Ya Pomeranchuk. Landau described the state of affairs and progress in the theory of nuclear reactors at the PGU NTS meeting on 10 February 1947, at which he presented a communication, "The current status of nuclear physics", partly reproduced below in connection with nuclear reactors [26]. Do not forget that Landau used the following code words: industrial resource — atomic energy; building No. 1 — uranium–graphite reactor; building No. 2 — heavy-water reactor; A-9 — natural uranium; A-93 — uranium-233; A-95 — uranium-235; A-98 — uranium-238; B-9 — thorium; 'cement' — graphite cladding, and Z-product — plutonium.

"The current status of nuclear physics

The volume of computational work needed for a successful resolution of the problem of utilization of industrial resources is extremely large.

This work runs into specific difficulties among which the most important are:

1. we do not know a number of experimental constants, and

2. we need to extend calculations further than is normally practiced in theoretical physics, where it is usually sufficient to establish the general relationship. The absence of a considerable number of experimental data and the impossibility of obtaining them in the near future forces theorists to make an effort toward the most complete and comprehensive use of the available data.

All computational work involved in the utilization of industrial resources can be classified into four relatively independent groups:

1. theory of building No. 1;

2. theory of building No. 2;

3. theory of processes occurring in the explosion itself;

4. analyzing phenomena occurring as a result of the explosion.

Moreover, there is another large group of issues relating to the theory of various methods of separation.

This last group of problems will not, however, be touched on in this report, as I did not work on them.

I shall concentrate first on the theory of building No. 1.

What occurs in building No. 1 is a combination of a number of complex phenomena. Fast neutrons ejected from A-95 nuclei during fission may either cause fission to start in other nuclei of A-9 or — most often — lose energy and slow down as a result of collisions with nuclei of the moderator. In the course of moderation of fast neutrons, as energy decreases from several million to several electron-volts, they undergo resonance absorption by nuclei of an A-9 isotope.

Resonance absorption is especially intensive in the range of neutron energies near 5 Volt, for reasons to be clarified somewhat later.

From the point of view of developing the chain reaction in the pile, the resonance absorption is very detrimental and its suppression is one of the main problems emerging in the practical implementation of buildings No. 1.

When neutrons are slowed down to even lower energies, on the order of the thermal energy of atoms in the crystal lattice (about 1/40 of one electron-volt), neutrons are absorbed, which is useful for the development of the basic reaction in A-95 nuclei and useless in A-95 nuclei of 'cement' and all sorts of harmful admixtures contained in the materials of the reactor. The reactor is designed as an array of rods made of A-9 and a hard moderator distributed around them, and thus constitutes an essentially nonhomogeneous system.

In fact, a number of properties of a realistic reactor can be understood by considering a simplified so-called homogeneous reactor in which the principal component is assumed to be spread uniformly throughout the volume of the moderator.

The theory of resonance absorption in the homogeneous reactor was mostly developed by I Ya Pomeranchuk. Pomeranchuk derived the law describing the effects of individual levels of A-98 on the resonance capture of neutrons. It was found that the resonance absorption probability is proportional to $\Sigma 1/E_i^{5/4}$, where E_i is the energy of the ith level and summation is carried over all levels.

It is clear from the above expression that the first low-lying level, with the lowest value of E, plays the most important role in resonance capture. However, since individual terms of the sum decrease rather slowly with increasing E_i, the upper levels also contribute substantially to the resulting resonance absorption.

In the specific case of A-98, the separation between the first level with an energy of 5 eV and zero-point energy is less than its distance to the next level. Consequently, the role played by the first level in resonance absorption is relatively high. However, to find the total resonance absorption it is necessary to know all lower levels of A-98. Measuring the effect of individual levels on the resonance absorption in conventional nuclear experiments is a very complicated procedure but can be carried out in a much simpler and reliable way in the pile itself.

The process of absorption of slow (thermal) neutrons with an energy of about the thermal energy of a crystal lattice is very complicated. The absorption of thermal neutrons is influenced by the chemical bonding between atoms in the crystal, the motion of atoms in the crystal lattice, and other complex factors of this type.

According to a communication by the American theorist Wigner, published in open press, *Journal of Applied Physics*, Nov. 46, attempts to conduct a theoretical analysis of absorption of thermal neutrons were made at the Metallurgical Laboratory (Chicago) but failed to provide positive results.

In view of the complexity and entangled pattern of the phenomena, we believe that the quantities characterizing the absorption of thermal neutrons must be determined experimentally, also carried out directly in reactors.

The main task of the theory of the atomic pile is the calculation of the real reactor, done on the basis of the characteristics of the assemblies and moderator that would be measured in the reactor itself. One of the important problems in the theory of the reactor is the one about the optimal arrangement of rods.

I proposed a method of calculations for a reactor in which the properties of rods are characterized by two parameters, whose values for a given rod must be taken from experiments. One of these parameters characterizes the properties of the rod in relation to the absorption of resonance neutrons, and the other, in relation to the absorption of thermal neutrons.

It was possible to find the dependence of the multiplication coefficient in the system on these parameters and thus solve the problem of optimal arrangement of the rods.

To determine the distribution of neutrons in building No. 1 and its insulation, and also its critical dimensions, we need to solve a complicated integral equation. However, A B Migdal suggested a considerably simpler method of calculations, in which the heterogeneous nature of the reactor is used for simplifying the equations. This approach made it possible to completely calculate the neutron flux in the insulated unit, and also the critical size and all other parameters of the unit. With the neutron field inside the structure known, it was easy to calculate the absorption of neutrons in the control rods. It is possible to assume here that cadmium absorbs all the thermal neutrons hitting it.

A difficulty arises in calculating the absorption of neutrons in control rods. Namely, it is not possible to utilize the diffusion equation because rod dimensions are comparable with the neutron path.

Landau and Pomeranchuk solved this problem having shown that the error caused by applying the diffusion equation is small and depends on $\log d/L$, where L is the neutron path, and d is the rod dimension.

To summarize the situation on the whole, we can say that at the moment we have developed methods for effectively solving all problems relevant to the theory of building No. 1.

The theory of buildings No. 2 is essentially different from that of building No. 1. The difference is caused by the fact that energy loss in collisions of neutrons with nuclei of D cannot be regarded as small — something we did in the case of C. (*Author's remark*: C *stands for graphite*.)

However, Landau and Pomeranchuk proposed a procedure that made it possible to reduce the problem of neutron moderation in deuterium to the diffusion equation.

The result was that the theory of building No. 1 could be transferred with small corrections to the case of building No. 2. [...]

Looking now at longer-term problems, we need to emphasize the following main tasks:

1. The problem of regeneration;
2. The problem of thermal explosion;
3. Research in those areas of nuclear physics that study ejection of new particles and search for new basic reactions.

Conventional reactors utilize the working material extremely inefficiently. The reason for this lies in the fact that the amount of the Z-product generated by the reaction is less than the initial amount of the useful A-95 component.

In principle, however, it is possible not only to utilize A-95 completely but even to utilize the entire product A-9.

Therefore, the problem of regeneration, i.e., the problem of complete utilization of the entire amount of the material A-9, is one of the main problems facing researchers.

In this connection, reactors that could reprocess B-9 into A-93 are of great interest since it is possible that the problem of regeneration would be solved more easily with these reactors.'' (*Author's note*: *for the continuation of the report on the A-bomb issue see Section 7*.)

No other reports or documents highlighting Landau's work on the theory of nuclear reactors were found in the archives of Rosatom or RF SSC ITEP.[1] It is possible

[1] As mentioned in the memorandum of A I Akhiezer and I Ya Pomeranchuk quoted in Ref. [107] on p. 547, L D Landau co-authored several reports on the theory of nuclear reactors:

L D Landau, I Ya Pomeranchuk ``Theory of moderation of neutrons in nonhydrogen moderators'', 1946. The report is kept in Lab. 2 and Lab. No. 3.

L D Landau, I Ya Pomeranchuk, A B Migdal ``Theory of lattices'', 1946. Report on this work is in Lab. 2 and Lab. No. 3.

L D Landau, I Ya Pomeranchuk, A D Galanin ``Large assemblies'', 1947. Report on this work is in Lab. 2 and Lab. No. 3.

therefore that this communication at the PGU NTS meeting is the only evidence of Landau's contribution to the development of the theoretical foundations of calculations for heterogeneous nuclear reactors. It is obvious that Landau, together with Pomeranchuk, found solutions for the most important and principal aspects of the theory of calculations for heterogeneous reactors. This conclusion is also implied by the "Expert evaluation of the calculations submitted by the USSR Academy of Sciences Laboratory No. 3 for designing the industrial facility" prepared by a commission of experts consisting of N N Semenov, I V Kurchatov, L D Landau, and Ya B Zel'dovich. The commission was set up by the NTS. The evaluation was presented to an NTS meeting on 5 April 1948 [39]. Comparing Landau's communication of 10 February 1947 with this expert opinion, we recognize Landau's impact on the contents of the latter, because he knew far more about the physical problems of heavy-water reactors than the other members of the commission. In this connection, we reproduce here the conclusion of the four academicians in full:

"Expert evaluation of the calculations submitted by the USSR Academy of Sciences Laboratory No. 3 for designing the industrial facility.

The designs of physical and technical heavy-water reactors developed in Laboratory No. 3 are based on the theory of reactors elaborated by the theoretical department of Laboratory No. 3 (Pomeranchuk, Galanin, Berestetskii). Thermotechnical aspects were Petrov's responsibility. The authors were in a difficult situation when elaborating the theory, as we still do not have the complete set of data on the materials used in the facility, data necessary for consistently working out a rigorous theory. For example, we still do not know the exact information on the position and properties of all resonance absorption levels of uranium-238, on the fission threshold of uranium-238, on the spectrum of primary fission neutrons, or on the inelastic neutron scattering by uranium.

For this reason, quantities entering into the calculations were in a number of cases not expressed as functions of nuclear constants but were found from experimental data obtained in the reactors. The laboratory has been unable so far to conduct its experiments for lack of sufficient amounts of heavy water; using experimental data measured by other researchers is a hindrance when an unbiased evaluation of the accuracy of data is attempted. Design calculations for piles using pure heavy water and uranium rods of various diameters at different distances between them require that the values of φ (the probability with which uranium captures neutrons moving at velocities corresponding to resonances) or the values of $1-\varphi$ (the probability of thermal neutrons not being captured by uranium in the rods) be found theoretically.

When calculating $1-\varphi$, the authors use the fundamental formula of the theory of assemblies derived by Gurevich I I and Pomeranchuk I Ya two to three years ago:

$$1-\varphi = B\rho^{3/2}/\sigma\,,$$

where ρ is the radius of the uranium rod, σ is the cross section area of heavy water falling at one rod, and finally B is a constant that can be rewritten as a product of two factors a and b, of which the former depends on the properties of the moderator, and the latter only on those of uranium itself. The formula is valid beginning with that radius of the rod at which the middle of the resonance line corresponds to a completely 'black' rod, i.e., practically all resonance-energy neutrons hitting the rod are absorbed by it. This assumption is definitely satisfied well for the chosen rod dimensions at the main resonance level of about 5 Volt and very probably is also satisfied for all resonances lying below 200 V. If, to the contrary, the rods absorb neutrons very weakly (this may be true for high resonance levels), then $\rho^{3/2}$ would be replaced by ρ^2 (the quantity proportional to the total mass of uranium) and the system would be better after recalculation from thick to thin rods (from the standpoint of $\nu\varphi\theta$) than the calculated one.

Another factor is more important: the above formula for φ holds only if $\rho \ll 1$ (l is the scattering mean free path in D_2O), which is never true in real systems.

However, there is another limiting case (equally unrealistic) of $\rho \gg l$, in which calculations are possible. The authors carried out the calculations using the stringent albedo theory [Halpern et al., *Phys. Rev.* (1938)].

For cylindrical rods this limiting case gives

$$1-\varphi = B^*(\rho\log\rho)/\sigma\,.$$

A correlation between these two solutions for small ρ/l and large ρ/l reveals that the solution for real values of ρ/l in the range between the two extremes cannot differ appreciably from that obtained with the former formula. It appears that calculations in this part do not deserve any criticism.

Then it was necessary to find the constant B; for this purpose, one pair of data was used which for the known system gives 1) the value of the multiplication coefficient, i.e., the product $\nu\varphi\theta$ in an infinite system, and 2) the quantity characterizing the spatial distribution of neutrons — the so-called Laplacian $\chi^2 = \nu\varphi\theta = 1/(L^2-\lambda^2)$, where λ is the moderation length, and L is the diffusion length of slow neutrons, depending on the absorption in uranium.

Assuming that ... is known, we can find from the above two quantities the value of ν and θ separately $[L^2 - L_0^2(1-\theta)]$; however, it remains unknown in what way the used value of $\nu\varphi\theta$ was obtained experimentally.

In calculating constants it was assumed that uranium and heavy water in initial experiments were ideally pure, while corrections were introduced in pile calculations that took account of their real purity, in accordance with our specifications.

The authors made another attempt to verify the values they obtained; for this Kurchatov gave them one value of φ measured in a uranium–graphite lattice. As was mentioned, $B = ab$, where a depends on the medium and can be found both for heavy water and for graphite, while b is a constant relating to uranium only. Calculations based on the data pointed out earlier and on those provided by Kurchatov resulted in practically perfect agreement (an accuracy of 5%), which to a certain extent confirms the correctness of the value of B obtained by the authors. Nevertheless, the amount of data is too small for us to be completely sure that the value of B is correct.

In addition, it is necessary to point out that the above experimental data both for heavy water and for graphite refer to rods 20 to 30 mm in diameter, and there is still no experimental proof that the method of calculations for thin rods is reliable. Direct determination of φ in the system of D_2O with thin rods would be very desirable.

The second theoretical problem reduced to determining θ, i.e., to the question about the absorption of neutrons by uranium immersed in heavy water.

The authors indicate that if the ratio of capture cross section to scattering cross section were small — that is, the rods were definitely not black in relation to thermal neutrons — then the diffusion equation used in the calculations would be simply an exact one. This is not true, however, since the capture cross section is of the same order of magnitude as the scattering cross section, so that a certain neutron concentration gradient arises near the rod surface; hence, using the diffusion equation instead of the integral equation in the case of this gradient produces errors.

The Fainberg brothers at Laboratory No. 2 evaluated the error for the planar and spherical cases using the simplest assumptions of monochromatic neutrons. The deviation in $1 - \theta$ does not exceed 10%, i.e., no more than 1% in θ.

In reality, however, higher accuracy of calculations is hampered not only by serious mathematical difficulties but also by unresolved physical problems, since neutrons in the vicinity of the rod are distributed over energy and not according to the Maxwellian law, plus the exact theory would incorporate energy exchange between thermal neutrons and heavy water. For this reason, it would be hardly possible to achieve a more exact calculation than the one reported by the authors.

Subsequently, it would be desirable to elucidate the sign of the error caused by employing the diffusion equation, which can probably be achieved without great difficulty.

In their calculations of the multiplication coefficient, the authors neglect the fission of uranium-238 by fast primary neutrons. Even though this effect is perhaps not too prominent, it still deserves attention, since no uranium-235 is consumed in this process.

The authors analyzed in detail the role played by the shell of the pile. In this part of the work, the uranium–heavy water lattice is considered as uniform and is described by the diffusion equation with constants averaged over the total volume. The error introduced by this approach appears to be very small. Strictly speaking, further calculations require that neutrons of all intermediate energies be considered. In fact, the authors use a simplified two-group technique — that is, a set of two differential equations describing the slow-down of fast neutrons to thermal energies and the diffusion of thermal neutrons. In reality, each fast neutron transforms into a thermal one with a probability equal to 1 after a certain number — quite large — of collisions with the moderator. A simplified two-group treatment corresponds to the assumption that a fast neutron may turn into a thermal one in each (single) collision, albeit with a correspondingly small probability. It appears that this simplification does not introduce a large error in the case where the diffusion length of neutrons in the shell is sufficiently high compared with the moderation length, and this is indeed the case in practical situations. Nevertheless, it is desirable to improve the method and determine its errors.

Calculations for atomic piles with heavy water and tubes cooled by ordinary water have also been done successfully by considering the diffusion equation in four media — U, Al, H_2O, D_2O.

The effect of Al and H_2O related to the absorption of thermal neutrons is taken into account, but the additional moderation of resonance neutrons by light water, acting more strongly than D_2O, is, however, ignored. If this factor was taken into account, the characteristics of atomic piles of the type considered would be somewhat improved in comparison with the calculations.

As far as thermotechnical calculations are concerned, the laboratory formulated a problem of designing the reactor in such a way that the temperature of the metal would not exceed 450 °C at rod midpoints, and 90 °C on the rod surface.

When it is the internal heat conductance of (thick) rods that is the limiting factor, the reactor output depends on the first condition, i.e., the metal temperature at midpoint. Correspondingly, it would be desirable to learn through experiments (e.g., by electrically heating the rods) how the metal behaves when the temperature at the midpoint rises to above 600 °C. In the case of thin rods, the limiting factor is the heat transfer from the surface, so it is desirable to achieve higher admissible surface temperatures.

The surface temperature was chosen in the project in such a way that heat transfer proceeded without boiling. When heat transfer is studied (this will be described further on), it is necessary to find the average volume of the vapor phase in the boiling mode at the surface in order to have an idea if it is possible (from the standpoint of controlling the nuclear chain reaction) to enhance heat transfer during boiling.

However, thermotechnical calculations in this assignment are again inadequate and their reliability is insufficient — partly because of the paucity of initial data.

In the case of longitudinal flow, the data reported by various researchers diverge by a factor of 1.5. In the case of transverse flow, there is no data on heat transfer in liquids; no rigorous theoretical calculation is possible; the extrapolation from data for the gas used in this work is unreliable. There is an urgent need for direct experiments under conditions close to those in the reactor. It is not clear what maximum possible water flow rate is admissible. The limits to which the flow rate and hydraulic head can be increased in the transverse flow case depend on the strength of the housing and partitions; to clarify this point, conceptional design accompanied by calculations of the most favorable high-strength designs with little use of aluminium (use of frame structures and so forth) is required. It is not clear if cavitation would limit flow rate.

It is likely that heat transfer could be forced more in the transverse version than the authors anticipate, but this would require additional experiments. Also, it would not be possible to conclude with any certainty without additional experimenting and conceptional design which flow mode (longitudinal or transverse streamlining) would be more favorable.

When choosing the rod thickness, the authors consider the feasible extent to which the isotope-235 can be used ('burn-up depth') and the daily yield of plutonium per tonne of heavy water as a much more difficulty available product.

The burn-up depth is smaller for thinner rods but the daily yield for them is higher.

Furthermore, increased flow rate and heat elimination from the surface will not increase daily yield in the case of thick rods (thicker than 20 mm) but will increase it appreciably in the case of thin rods.

According to the authors' data, in the regime with the temperature in the middle of the rod at 460 – 500 °C, that on the surface at 70 – 90 °, and water flow rate of 6.5 m/s, 20-mm rods will reveal an 18% burn-up fraction and produce 53 g/day (at 70 MW power). Rods 10 mm in diameter will reveal a 9% burn-up fraction and produce 200 g/day (at $\sim$ 200 MW power), plus the process could be intensified even more. Laboratory No. 3 selected the 20-mm diameter mode. In our opinion, the issue of thin rods required thorough analysis.

We note that with the chosen rod diameter, plutonium is extracted and the process is correspondingly interrupted every 14 days. Thinner rods will necessarily be taken out more frequently. Therefore, on the one hand, it is necessary to specify the structural side of the unloading technology, taking into account the need to cool down the rods heated by the radioactivity of fission products. On the other hand, the issue of making the specifications for plutonium less stringent arises again, as this would allow less frequent withdrawal of rods, provided plutonium would be subsequently purified of the isotope.

Conclusions:

1. Since the laboratory did not have sufficient amounts of heavy water, it did not run the necessary experiments and had to restrict itself to the theoretical investigation of the problem.

Very much valuable work has been conducted which led to correct notions of how the nuclear characteristics of deuterium piles depend on lattice parameters (the diameter and spacing of rods).

2. A number of simplifying assumptions had to be made for quantitative calculations, but the error introduced by this approach cannot be evaluated, although it appears to be small. It is desirable that the sign of error introduced by each simplifying assumption be determined.

3. The numerical value of the constant in the formula for φ was determined on the basis of the known but extremely limited experimental material (of outside origin).

It would be very welcome if φ were measured in a direct experiment in the $U-D_2O$ system with a small number of assemblies, for example, by measuring the β activity of uranium in cadmium-plated assemblies irradiated by an external source of neutrons.

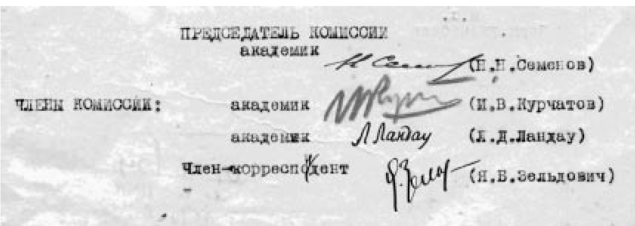
4. Fission of uranium-238 by primary (fast) neutrons was not taken into account. This problem is to be resolved by Laboratory No. 2.

5. Heat transfer calculations are unreliable, especially under the conditions of transverse flow, and cannot be theoretically improved in principle. The necessary experiments need to be run urgently, as do experiments and calculations that would clarify the feasibility of forcing the flow, which may increase the daily production of plutonium in thin rods.

It is necessary to investigate the behavior of uranium at temperatures at the rod center above the nominal value, heat transfer, and density of water in the case of surface boiling.

6. It is necessary to return to a thorough analysis of choosing the rod diameter for the project because, in spite of a shallower burn-up fraction, thin rods (under 20 mm in diameter) allow, at least in principle, an increase in daily output.

7. Forcing the process appreciably increases the role of down-time caused by unloading uranium and extracting plutonium. For piles with heavy water, therefore, the output can be boosted especially well if one accepts a higher content of the element-240 and subsequent electromagnetic purification.''


ПРЕДСЕДАТЕЛЬ КОМИССИИ
академик (Н.Н.Семенов)
ЧЛЕНЫ КОМИССИИ: академик (И.В.Курчатов)
академик (Л.Д.Ландау)
Член-корреспондент (Я.Б.Зельдович)

This evaluation contains the following ''Appendix to the opinion of a commission of experts on the design of the heavy-water pile of the USSR Academy of Sciences Laboratory No. 3''.

''This Commission suggests appending the following to the section with conclusions:

1) In item 3 after the words ''experimental material'' add ''Nevertheless, testing the value of the constant using the exponential experiments on an A-9–graphite assembly provides a strong confirmation that the value established above is correct.''

2) In item 5 begin the last sentence, omitting the word ''necessary'' and putting in ''It is desirable for further forcing.''

3) Add two more items to the conclusions:

8. Consider calculations mentioned in items 1, 2, 3, and 4 to be adequate for the design, because calculation errors are small and are likely surpassed by the possibilities resulting from adjustments. The necessary corrections will be added to the project after experiments with F.k.

4) As for choosing the most favorable rod diameter, the answer will stem from the solution found for uranium unloading and the design of its mounting.

Signed by N Semenov.''

(*Author's comment*: *The above appendix was forwarded to B S Pozdnyakov at the PGU NTS as a document with ref. number No. 768sd on 29 December 1947*; *it can be found in the NTS protocol No. 115*; *F.k. — physical pile*.)

Reading this opinion of experts, we recognize rather clearly Landau's influence on its contents, first of all through those subtleties of physics and heat technology of heavy-water reactors that are emphasized in the text. It cannot be excluded, though, that some other scientist on the staff of Laboratory No. 3 prepared this text, e.g., I Ya Pomeranchuk, and Landau could have discussed it with A I Alikhanov. However, this is no more than a hypothesis, as we have no direct evidence of this.

Having considered the above evaluation, the NTS came to the following decision at its meeting on 5 April 1948 [39]:

''In accordance with the assignment of the Scientific and Technical Council (protocol No. 89), the Commission formed of Cdes. Semenov N N, Kurchatov I V, Landau L D, and Zel'dovich Ya B made an examination of the theoretical calculations performed at Laboratory No. 3 and used it as a basis for the design assignment for an industrial-scale unit with the product 180 (the text of the decision of the commission of experts is attached).

According to the decision of Cde. N N Semenov's commission of experts, the theoretical calculations of the USSR Academy of Sciences Laboratory No. 3 for designing the industrial-scale facility are sufficiently accurate and contain no large errors.

The assumptions made for calculations are not significant and may be surpassed at the expense of the facility control system.

The Commission considers it necessary to conduct a number of additional experiments on the pilot unit to improve the accuracy of thermotechnical calculations as the amount of experimental data in this field is insufficient and this part of the calculations is insufficiently reliable.

Having heard the communication from Cde. Semenov N N, the Scientific and Technical Council resolved:

1. To take into consideration the final report of the commission of Cde. Semenov N N and charge Cde.

Table 3.

Job leaders and executive scientists	Main stages of work	Location	Deadlines for stages	Final result of project
"Burn-up processes in jet engine" 1. Development of chain reaction in the course of burning				
Leader L D Landau, Prof. Executing scientists: E M Lifshitz, Prof., and theoretical groups at Laboratory No. 2 and Institute of Chemical Physics	1. Equations of state of matter and envelope at temperatures and pressures produced in the course of chain reaction	Institute for Physical Problems in collaboration with Laboratory No. 2 and Institute of Chemical Physics	1 July 1947	Preliminary calculation of efficiency
	2. Taking account of radiative heat transfer			
	3. Taking account of expansion process			
	4. Taking account of matter burning out in action			

Alikhanov A I with taking into account the argumentation of the commission of experts when working on the project of the industrial-scale unit.

2. Charge Cde. Alikhanov A I with taking into account, while working on the program of experiments at the pilot facility, the comments and conclusions of the commission of experts referring to the experiments required for designing the industrial-scale facility, and also with speeding up the conduction of experiments for determining φ in accordance with the plan of research of Laboratory No. 3 [...]."

At the beginning of 1947, Landau started studying processes taking place during the explosion of an A-bomb and determining its efficiency and thus was unable to find time for the theory of nuclear reactors.

7. Participation in computational justification of the first Soviet atomic bomb

As follows from archival documents, the work on developing the first Soviet atomic bomb was stringently regulated by governmental decisions and those of the Special Committee and the PGU. Until mid-1946, the entire effort concentrated on Laboratory No. 2. To carry out the studies into the A-bomb in Laboratory No. 2, the Design Bureau No. 11 was established on 9 April 1946 [55], which subsequently grew into an independent research center. Already three months later the resolution of 21 June 1946 gave KB-11 the following assignment [56]:

"1. Design Bureau No. 11 (headed by Cdes. Khariton, Zernov) is charged with:

a) development, under the scientific guidance of the USSR Academy of Sciences Laboratory No. 2 (Academician Kurchatov), of two versions of "Jet engine S" ('RDS' for short): with heavy fuel utilization (version S-1), and with light fuel utilization (version S-2)."

Comment by compilers of the document: *heavy fuel — plutonium, light fuel — uranium-235*.

KB-11 was ordered to submit for state-class testing one copy of a verified and manufactured RDS in the S-1 version by 1 January 1948, and in the S-2 version by 1 June 1948 (these deadlines were subsequently extended). A CM resolution [57] charged the Special Sector of the Institute of Chemical Physics of the USSR Academy of Sciences with "carrying out the theoretical and computational works on the task orders of Laboratory No. 2." As we see from the resolution, the deadlines for creating the RDS were absolutely unrealistic — a year and a half for an exceptionally complicated and difficult undertaking.

On 30 November 1946, as formulated by the Resolution of the USSR Council of Ministers No. 2557-1069ts "On the plan of research of the Institute for Physical Problems of the USSR Academy of Sciences and measures to assist the Institute", the IPP obtained the first governmental assignment on the A-bomb [57]. By the way, this same resolution envisaged in item 2 that "the laboratory of Corresponding Member of the USSR Academy of Sciences Cde. Aleksandrov A P (with all its staff, equipment, and materials) be transferred from the Leningrad Physico-Technical Institute of the USSR Academy of Sciences to the Institute for Physical Problems of the USSR Academy of Sciences."

Item 1c) of the resolution stated this: "The following work will be regarded as first priority: [...]

c) theoretical studies of processes involved in the nuclear reaction in the critical mass (the work was conducted by the USSR Academy of Sciences Laboratory No. 2 and the Institute of Chemical Physics)."

The plan of classified research at the IPP, approved by the Government for 1946 and for the 1st half of 1947, formulated the main stages of the project [57] listed in Table 3.

It must also be pointed out that the approved plan for nonclassified research at IPP included studying the properties of matter at ultralow temperatures; the program was headed by two professors — A I Shal'nikov and L D Landau.

On 2 June 1947, IPP Director A P Aleksandrov and head of the IPP theoretical sector L D Landau presented communications to the PGU NTS meeting concerning the "Plan of research at IPP for 1947, comprising computational and theoretical studies in nuclear physics" (the plan reproduced below shows that these nuclear physics investigations dealt with the atomic bomb) [28].

The PGU NTS passed the following decisions:

"According to information provided by Cde. Aleksandrov A P and Cde. Landau L D (the material received from Cde. Landau L D is attached), the computational and theoretical group of the Institute for Physical Problems, together with the theoretical departments of the Institute of Chemical Physics and Laboratory No. 2, plans to carry out the following computational and theoretical works:

a) Calculate the total energy release and efficiency as functions of various factors, especially dimensions, initial density, and insulation thickness.

In connection with the above, develop the methodology of calculations, establish the theoretical equation of state of the material, find the thermal conductivity of the material as a function of temperature and density, and the neutron multiplication coefficient in nuclear fission as a function of density.

b) Elucidate the potential thermal effect of light elements and develop general methods for approaching the problem and methods of calculations.

Having discussed the report of Cde. Aleksandrov A P on the aggregate plan of works for 1947 and the communication from Cde. Landau L D on the plan of computational and theoretical work in compliance with the assignment from the Council of 10 February 1947, the Scientific and Technical Council resolved:

1. Approve the aggregate plan of experimental, computational and theoretical works for the IPP submitted by Cde. Aleksandrov A P, and append to this plan the additional development of methods of measurement of expansion coefficients of the Z-product and of the appropriate measurement instruments (plan of research for the IPP is attached). [...]

4. It is concluded that the plan of theoretical studies in nuclear reactions submitted by Cde. Landau L D does not cover all aspects formulated by the Scientific and Technical Council (assignment to Cdes. Landau L D, Zel'dovich Ya B, Pomeranchuk I Ya, Tamm I E).

5. Confirm the decision made by the Scientific and Technical Council on 10 February 1947 concerning the development of a long-term plan of theoretical investigation in nuclear reactions and charge the commission formed of Cde. Kurchatov I V (chairman), Cdes. Alikhanov A I, Semenov N N, Khariton Yu B, Leipunskii A I, Kikoin I K, Landau L D, and Zel'dovich Ya B with compiling and discussing the above plan in a month's time and submitting its proposals to the consideration of the Council.''

Appended to the NTS protocol is the plan for the IPP work on the A-bomb for 1947, reproduced below:

``Plan for the IPP of the USSR Academy of Sciences for research in 1947 (classified programs).

Problem: calculation of the total energy release and efficiency as a function of various factors, especially dimensions, initial density of the material, and insulation thickness.

Leader of program: Academician Landau L D; executing scientists: Lifshitz E M, Khalatnikov I M, Computation Bureau of Meiman N S, in collaboration with the theoretical departments of the USSR Academy of Sciences Institute of Chemical Physics and Laboratory No. 3.''

Furthermore, we can get acquainted here with L D Landau's handwritten abstracts ``On the work plan of the department of theoretical physics of the Institute for Physical Problems'' that he delivered at an NTS meeting (manuscript, mb. T-1089sd of 2 June 1947), namely:

``1. Main phenomena unfolding in working jet engine

a) multiplication of neutrons

b) emission of radiation

c) expansion.

2. Method of approximate calculation of efficiency

3. Thematic and calendar plan of department's research (attached)

4. General status of special projects on theoretical physics and correlation of research plans of the institutes involved

5. Fundamental problems of nuclear physics

a) basic difficulties in the theory of the nucleus

b) insufficient experimental information.''

Signed by L Landau (manuscript, written in Landau's handwriting). This is probably the only document written personally by Landau and archived at Rosatom.

The ``Plan for special research projects for 1948'' approved by a resolution of the USSR Council of Ministers on 6 April 1948 charged the IPP with promoting the following works during the 1st and 2nd quarters of 1948 [58]:

``18. Calculation of efficiency for a sphere with an infinite shell. Science supervisors Corresponding Member A P Aleksandrov and Academician L D Landau, executing scientists I M Khalatnikov and E M Lifshitz.''

The computational analysis of processes occurring during an atomic explosion is a very complex but at the same time interesting problem for any theoretical physicist. Landau in his appearance before an NTS meeting on 10 February 1947 [26] characterized the phenomena unfolding in an atomic explosion as follows:

``[...] Processes that take place during an explosion are very complicated and tangled.

At the moment we have conducted a large amount of preparatory work and marked out the stages of the basic calculation of the explosion efficiency, i.e., the dependence of the energy released on the degree of supercriticality achieved when segments of the gadget are brought together.

The absence of certain experimental information, for instance, of the angular dependence of the scattering of neutrons by A-9 nuclei, does not allow a quantitative calculation. Therefore, here, just as in the theory of buildings No. 1 and No. 2, one needs to introduce into the calculation characteristic macroscopic constants — the effective cross section σ_{eff} of neutron scattering and the characteristic time τ determining the rate of neutron multiplication in matter. Even though calculations based on the introduction of effective quantities cannot be very accurate, practical experience has shown that the errors they introduce are acceptably small.

Consequently, if σ_{eff} and τ are found from laboratory experiments with sufficient accuracy, one has every reason to believe that the theoretical calculations based on them would be sufficiently reliable.

The theory of the effect of an explosion was developed by Ya Zel'dovich and his group. The theory of the shock wave is based on the method of calculation that I suggested. This method makes use of the property of self-similarity of the spherical shock wave, which continues to hold as long as the pressure in the wave remains much higher than the atmospheric pressure.

Zel'dovich also showed that the distinctive feature of the atomic explosion is that in this case a considerable part of this energy converts into radiation. Starting with this concept, Zel'dovich was able to develop the theory of the cooling wave. [...]

The issue of the possible triggering of a thermal explosion and its propagation was subjected to preliminary theoretical analysis by Zel'dovich and Khariton.

They noticed that in the case of nuclear reactions the energy transforms mostly into radiation, not into the thermal energy of motion of nuclei and electrons.

As a result, matter is heated by the nuclear reaction only relatively insignificantly. For example, of the 200 MV released by fission, only 18 kV goes to heating matter, while the rest of the energy transforms into the energy of radiation.

This factor makes it very difficult to produce a thermal explosion. (*Comment of the author of the article*: *thermal explosion stands for* '*nuclear explosion*'.)

There is another factor, however, which makes a thermal explosion feasible in principle. Namely, it was found that the transfer of nuclear energy into radiation is not an instantaneous process but one that requires a certain period of time. If the rate of reaction is higher than the rate of transformation of energy to radiation, the thermal explosion may occur before a considerable part of the energy is lost to radiation.

At the moment, only one reaction seems to be known with which this process can be implemented — the reaction _____. (*Comment of the author of the article*: *not specified*.)

Zel'dovich et al. carried out preliminary calculations for this reaction but so far we cannot say with complete confidence that this reaction is feasible.

Complicated and time-consuming computations are needed to reach this level of confidence.

One of the main tasks of today's physics is the study of new particles and particles possessing very high energies, and the reactions they cause.

In addition to the enormous interest this has in principle, the results of this work may lead to new ways of identifying more efficient reactions of the basic type.

Among other things, no powerful accelerators are in operation yet in this country. We need to expand work as much as possible in cosmic ray physics where very valuable results have been obtained — Alikhanov and Alikhan'yan discovered new particles with a mass considerably higher than that of the electron and which seem to interact very actively with atomic nuclei.

To conclude this report, I would like to direct attention to one organizational aspect.

The work we do requires complex and labor- and time-consuming numerical calculations.

To conduct this work, only one computation bureau has been organized so far, the one headed by Semendyaev, but it is extremely overloaded with work.

We are hopelessly behind time with the organization of the second computations bureau, although I was able to gather a fully staffed team for this bureau.

Computation bureaus are a prerequisite for the rapid execution of tasks.''

On 5 June 1948, a session of the Special Committee gathered to discuss two important topics: ''1. On additions to the plan of works of KB-11 (Cde. Khariton), and 2. On additional task orders to the plan for special research work for 1948 (Cdes. Pervukhin, Vavilov, Tikhonov, Petrovskii, Beria)'' [59]. Invited to the sitting of the Special Committee were Academicians S I Vavilov, S L Sobolev, L D Landau, A P Vinogradov, I G Petrovskii, the USSR AS Corresponding Members Yu B Khariton, A P Aleksandrov, A N Tikhonov, Ya B Zel'dovich, and DSc in physics and mathematics K I Shchelkin. For the first time in the existence of the Special Committee Landau was also present at this sitting which, on the one hand, was a huge surprise as far as Landau was concerned but, on the other hand, constituted a wise decision.

Even though this issue was not in the plan of works for the IPP for 1949, a decision by B L Vannikov, head of the PGU, entrusted Landau with making an examination of the theoretical calculations done at KB-11. On 9 June 1949, a discussion was convened at KB-11 ''on issues of RDS-2, RDS-3, RDS-4, and RDS-5'' [60] in which B L Vannikov, I V Kurchatov, Yu B Khariton, and others took part. Among others, the following decisions were taken in relation to Landau's work:

Concerning RDS-2: ''1. Send the theoretical calculation for expert evaluation by Academician Landau, Academician Sobolev, and Cde. Tamm.''

Concerning RDS-3: ''Send the theoretical calculation for expert evaluation by Academician Landau and Academician Sobolev.''

Vannikov and Kurchatov reported to Beria on 15 June 1949 on the decisions taken at the meeting at KB-11, including the assignments to make an examination of theoretical calculations by these academicians, in a special memorandum [61].

Two USSR Council of Ministers Resolutions No. 1989-773ts/sd [62] and No. 1990-774ts/sd [46] of 10 June 1948 were signed into action on the basis of the decisions of the Special Committee of 5 June 1948. Resolution No. 1989-773ts/sd ruled:

''1. Charge KB-11 (Cdes. Khariton and Zernov) with:

a) completing before 1 January 1949 a theoretical and experimental verification of data on the feasibility of implementing the following RDS designs: RDS-3, RDS-4, RDS-5 and, before 1 June 1949, RDS-6; [...]

c) developing before 1 January 1949 a conceptual design of RDS-6 based on the available preliminary data;

d) carrying out calculations, in collaboration with the Institute for Physical Problems (Academician Landau), and comparing the efficiency of five possible versions of the RDS with the following deadlines: concerning RDS-1 and RDS-2 — by 1 November 1948; concerning RDS-3 — by 1 January 1949; concerning RDS-4 — by 1 May 1949, and concerning RDS-5 — by 1 June 1949.

The findings, conclusions and recommendations have to be submitted to the Special Committee in the course of meeting the deadlines.''

The above assignments were additionally modified and specified in the governmental Resolution No. 1990-774ts/sd partly quoted below [46]:

''2. Charge the Institute for Physical Problems of the USSR Academy of Sciences (Cdes. Aleksandrov and Landau) with calculating the efficiency of various versions of RDS using the data provided by Laboratory No. 2 (Cdes. Khariton and Zel'dovich) with the following deadlines:

a) for RDS-1 and RDS-2 — by 1 November 1948;
b) for RDS-3 — by 1 January 1949;
c) for RDS-4 — by 1 May 1949;
d) for RDS-5 — by 1 June 1949. [...]

4. Obligate the Institute of Geophysics (Cdes. Shmidt and Tikhonov) to ensure the execution of all necessary computations according to the task orders of the Institute for Physical Problems of the USSR AS (Cdes. Aleksandrov and Landau), for which purpose a Bureau of Mathematical Calculations will be set up with a staff of 30 employees. Entrust Corresponding Member of the USSR Academy Tikhonov with a task of giving leadership to the Bureau of Mathematical Calculations.''

The same resolution awarded a prize of 100 thousand rubles to each head of the theoretical and computational subdivisions, while 200 and 300 thousand rubles to the two teams, respectively; additionally, the two future academicians A D Sakharov and A A Samarskii were each assigned a living room.

One can learn of the evaluation of work done by Landau's group on calculating A-bomb efficiency by reading the decision of the ''meeting on issues of KB-11 in which B L Vannikov and I V Kurchatov took part while visiting the 'object' between 23 and 28 December 1948 [63].'' Section 9 of this decision reads:

"IX. Concerning efficiency

An approximate method for calculating the efficiency of the products was developed and presented. The method makes it possible to single out the effects of various characteristics of the design on efficiency. Absolute values of efficiency may somewhat deviate from calculated predictions.

The refined absolute values of efficiency will be obtained in the nearest future, after Cde. Landau completes the work on improving the fundamental approach to calculating efficiency.

Decision

Charge Cde. Sobolev S L together with Cde. Zel'dovich Ya B with checking the state of affairs with the project conducted by Cde. Landau and report the results of the assessment and the scheduled date for completing the work to Cde. Vannikov B L."

In section "X. Aspects of the combined design version" it was noted: "2. Preliminary calculations of efficiency have been carried out that gave values slightly lower than those for RDS-1. One needs to take into account here that this design version may provide a more efficient utilization of the available amounts of Z and A-95. Calculations will be improved in the 1st quarter of 1949."

From the standpoint of the amount of work put in by Landau's group on the A-bomb, it is instructive to look at the letter of 3 March 1949 from Yu B Khariton to B L Vannikov concerning awards to the participants of the project on the creation of the A-bomb; item 4 of the letter [64] reads:

"The USSR CM Resolution No. 1990-774ts of 10 June 1948 foresees the execution of theoretical and computational works on designs of the RDS and awards for theoretical physicists and mathematicians for completing their assignments on time. [...]

Item 4. A theory of efficiency calculations was developed and efficiency calculations were carried out for RDS-1, RDS-2, and RDS-3 versions. These calculations consider: multiplication of neutrons, energy release, its conversion to radiation and diffusion of the radiation, expansion of the active material, motion and implosion of the shell.

In view of extreme complexity of the problem, the calculations had to be approximate. The calculations were discussed and approved at the seminar of Academician Sobolev. A program is outlined for mathematically increasing the accuracy of the solution (Tikhonov's group).

Calculations yielded approximate values of expected efficiency: RDS-1 — (...), RDS-2 — around (...), RDS-3 — an intermediate value between those of RDS-1 and RDS-2, depending on the ratio between Z and A-95. The dependence of efficiency on structural factors has been clarified.

Efficiency calculations were conducted by Landau's group mostly in collaboration with mathematicians of Meiman's mathematical bureau (at the Institute for Physical Problems).

Task orders for calculations and structural conclusions — Zel'dovich's group (KB-11).

The results of the work reside in the IPP reports Nos 12 of 13 September, 13 of 28 October, 13a of 19 November, 14 of 19 November, and 15, 16, 17 of 28 December, and in the KB-11 report No. 17/c of 20 August 1948.

Remaining to be completed are calculations for RDS-4 and 5; in this connection, the effect of various factors on efficiency will be carried out by Landau's group; a mathematical improvement of the solution is also anticipated (Tikhonov's group). [...]

In view of the above, I request your permission to award bonuses:

to Zel'dovich's group (Laboratories of Frank-Kamenetskii and Zababakhin at KB-11, Kompaneets at ICP) — [...]

to Landau's group (inclusive of Meiman's bureau) at IPP — 50% of the total amount, i.e., 50 thousand rubles to the group leader and 100 thousand rubles to staff members [...]."

IPP Director A P Aleksandrov may have been unknown of this letter from Yu B Khariton because he addressed M G Pervukhin on 19 March 1949 with a request concerning the deadlines on projects involved in the theory of efficiency of the A-bomb [65]:

"According to the USSR CM Resolution No. 1989-773ts/sd of 10.06.1948, the Institute for Physical Problems is responsible for theoretical work and efficiency computations as individual particular tasks listed in the governmental decision. These tasks were executed accordingly and the results were duly submitted.

At the moment, Yu B Khariton has suggested that the institute, instead of calculating particular cases, find the complete solution to the efficiency problem as a function of a number of factors. This completely changes the scale of both theoretical and computational works which can be effected within new deadlines that are imposed by the output capabilities of the computation bureau.

May I ask you to contact the USSR Council of Ministers on the matter of setting the new deadline as 1 July 1949 in view of the change of task, to replace the date set in the governmental decision on particular cases as 1 June 1949."

A month after writing this letter, A P Aleksandrov presented his report on accomplishing the plan of the research work at IPP in 1948 and on the research plan for 1949 at a PGU NTS meeting on 25 April 1949; the report said [66]:

"Regarding the theoretical work, calculations of the efficiency of the object were conducted in accordance with the plan agreed on with Yu B Khariton, and in compliance with the decisions of the Government. All theoretical work and all computations met the deadlines specified in the plan.

All the reports were submitted to Yu B Khariton (report Nos 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, No. 11 with additional clauses, Nos 12, 13, 13a, 14, 15, 16, 17 with an additional clause).

Theme supervisor L D Landau, head of computation bureau N S Meiman."

In the "Brief report on the status of work at KB-11 as of 15 April 1949" signed by Yu B Khariton and K I Shchelkin, the following has been found concerning the work of Landau's group [67]:

"The following projects were completed by 15 April:

1. The general theory of the product has been elaborated (head of project, Corresponding Member of the USSR AS Cde. Zel'dovich Ya B) and includes the following sections:

a) theory of the converging detonation wave in explosives;

b) theory of converging shock waves in metals;

c) theory of compressibility of metals at pressures of several million atmospheres;

d) theory of efficiency of RDS-1 (a number of issues were developed by Academician Landau L D according to the task orders of KB-11); [...]."

Documents outlined in this section indicate that Landau was fully aware of all the theoretical problems involved in the work on the first and all subsequent design versions of atomic bombs and participated actively in their computational and theoretical justification.

8. Participation in physics calculations for the first Soviet hydrogen bomb

The specific features of the process of developing the first hydrogen bomb (H-bomb) in the USSR were, first, the high political value staked on it, second, the exceptional scientific and technological complexity, third, the participation of a large number of research, planning and design, and industrial entities and of outstanding Soviet scientists and engineers, and fourth, an exceptionally high level of secrecy. Taking part in the work on proving the feasibility of the design of the first Soviet H-bomb were such first-class physicists as I V Kurchatov, Yu B Khariton, K I Shchelkin, A D Sakharov, V L Ginzburg, L D Landau, Ya B Zel'dovich, I E Tamm, Yu A Romanov, G N Flerov, I M Frank, mathematicians N N Bogoliubov, L V Kantorovich, A N Tikhonov, K A Semendyaev, A A Samarskii, N N Yanenko, and many others. The H-bomb could not be produced without manufacturing on an industrial scale lithium-6, deuterium, tritium, and their compounds as the basic components of thermonuclear weapons, or without methods needed to extract tritium from irradiated lithium. It can be claimed without exaggeration that developing the hydrogen bomb was the pinnacle of the theoretical and experimental physics and technology that Soviet specialists were able to master.

We need to remark that the first mention of the H-bomb, under the code name RDS-6, dates back to 5 June 1948 when the matter of organizing the creation of the H-bomb was discussed at a meeting of the Special Committee of the USSR Council of Ministers [59]. The scientific supervisor of the Soviet Atomic Project, I V Kurchatov, was at the time at plant No. 817 and busy commissioning the first industrial-scale reactor, and for this reason was unable to take part in this meeting. The Special Committee took two decisions concerning RDS-6. KB-11 was assigned the task of "carrying out [...] a theoretical and experimental assessment of data on the feasibility of implementation of the designs [...] before 1 June 1949 — RDS-6"; "1c) by 1 January 1949 develop on the basis of the available preliminary data a conceptual design of RDS-6." These two decisions were included in full in the governmental Resolution No. 1989-773ts/sd "On additional clauses to the plan of works at KB-11" dated 10 June 1948 [62].

The discussion in principle of various design approaches to the H-bomb took place on 21 December 1948 at a meeting of the Laboratory No. 2 NTS devoted to the KB-11 works and chaired by I V Kurchatov. It heard the reports of heads of research groups, Ya B Zel'dovich (ICP) and I E Tamm (PIAS), on the results of studying if the fusion of light nuclei could be used to design various versions of the H-bomb [68]. The protocol of this meeting of the NTS stated:

"The Council is of the opinion that the results reported by both groups are of considerable interest, especially the system proposed by Cde. Sakharov (Tamm's group) of a column made of layers of heavy water and A-9 which, according to preliminary calculations, could detonate at a column diameter of about 400 mm. A special advantage of this system is the possibility of using heavy water instead of deuterium, thus making it unnecessary to deal with hydrogen at low temperatures.

The Council has ascertained that the volume of computational and theoretical work needed to clarify details concerning the possibility of deuterium detonation (the work of Zel'dovich's group) is quite high, and has charged Cde. Sobolev, together with Cdes. Tikhonov and Petrovskii, with elucidating the possibilities of applying some mathematical procedures which would allow speeding up the work. [...]"

The decisive stage of the work on the H-bomb was the period of 4–9 June 1949 when B L Vannikov and I V Kurchatov organized a meeting at KB-11 (Arzamas-16) at which the leading scientists of the Atomic Project were present: Yu B Khariton, M G Meshcheryakov, deputy head of the PGU A S Aleksandrov, KB-11 Chief P M Zernov, K I Shchelkin, and Ya B Zel'dovich; the meeting discussed the directions of further research in using energy transformations with light nuclei and the creation of RDS-6 version of H-bomb [69]. Also invited to this meeting was A D Sakharov. The concluding part of the decision of the meeting stated firmly that: "Answering the question of whether a nuclear explosion using the energy of light elements is possible or not will require a wide range of theoretical and experimental research efforts, as well as developed technology for manufacturing materials needed for these purposes. The amount and nature of these studies will demand a concentration of great scientific power... ." The participants at the meeting outlined the following areas of research: nuclear reactions of light nuclei in RDS-6; the possibility of initiating RDS-6 with the aid of an atomic bomb and conventional explosives; use of the explosion of an atomic bomb to generate data relevant to the work on the H-bomb, and gas dynamics of the process. In addition to the theoretical work, the outlined plan of action included developing the industrial technology for producing tritium, lithium-6, lithium deuteride, and uranium deuteride required to build RDS-6.

Appended to the decisions of the meeting was a handwritten "Plan of research works on developing RDS-6 for 1949–1950" prepared, judging by the handwriting of the author, by A D Sakharov and signed by B L Vannikov, I V Kurchatov, M G Meshcheryakov, Ya B Zel'dovich, Yu B Khariton, P M Zernov (Chief of KB-11), K I Shchelkin, V I Alferov, and A D Sakharov. This plan consisted of a number of sections, including a section "A. Theoretical studies" which listed the following:

"Study of the mechanism of propagation of a detonation wave in a layered system.

Study of the instability of a layered system when traversed by high-temperature and low-temperature shock waves.

Problem of initiation of a detonation wave in a layered system.

Study of potential high-temperature detonation in deuterium. [...]

Executing scientists:

USSR AS LIP (Belen'kii S Z, Ginzburg V L, Zel'dovich Ya B, Kompaneets A S, Sakharov A D, Tamm I E)

Author's note: these scientists are listed as belonging to LIP — see below.

USSR AS IPP (Landau L D)

Mathematical Institute of the USSR Academy of Sciences (Petrovskii I G, Gel'fand I M, Semendyaev K A)

Institute of Geophysics (Tikhonov A N)

KB-11."

Foreseen in the plan were also experimental studies (determination of nuclear constants of interaction for heavy hydrogen, tritium, and helium: $H^2 + H^2$, $H^2 + H^3$, $H^3 + H^3$, and $H^2 + He^3$, the study of the spectra of neutrons produced in these reactions, etc.) and technological work on the production of tritium, lithium-6, and lithium deuteride.

On the basis of the results of this meeting, B L Vannikov and I V Kurchatov addressed a detailed memorandum dated 15 June 1949 to L P Beria with a draft resolution of the USSR Council of Ministers specifying the efforts to develop RDS-6 [61]. The memorandum said:

"Theoretical studies conducted currently at FIAN have failed to provide an exhaustive answer to the question if the energy of light nuclei (deuterium, tritium) transformations could be used for practical purposes. Neither have the first theoretical results provided initial data required for starting work on the conceptional design project."

The management of the Atomic Project had to be informed about the state of affairs, as an explanation was required why the deadlines of the USSR Council of Ministers Resolution [69] on submitting the conceptional design project of RDS-6 by 1 January 1949 were not met. Furthermore, the memorandum suggested some new organizational options. First, it was proposed to concentrate the main research efforts on designing RDS-6 in Laboratory No. 2; second, to nominate Academician I V Kurchatov as scientific leader of all theoretical and experimental projects; third, to move I E Tamm's group from PIAS and Ya B Zel'dovich's group from ICP to Laboratory No. 2. In addition, it was deemed expedient to organize the base of experimental work on studying reactions of light nuclei at Laboratory No. 2, with M G Meshcheryakov becoming scientific leader of the experimental program. However, we now know that these intentions were not implemented.

We have every reason to conclude, therefore, that the period of intense work on thermonuclear weapons began in mid-1949, not long before the test explosion of the first Soviet plutonium bomb. The test explosion of the first hydrogen bomb was still 4.5 years away, years of high-pressure work by large bodies of specialists.

At the early stage of the Atomic Project, Soviet scientists worked on two construction schemes of the H-bomb . These versions of the H-bomb went by exotic names which, first, satisfied security requirements, and, second, reflected their conceptual designs. The first scheme type, known as 'tube', was developed by Ya B Zel'dovich's group at USSR AS Institute of Chemical Physics (ICP). In addition to Ya B Zel'dovich's group, also taking part in the 'tube' research were L D Landau's group at IPP, I Ya Pomeranchuk's group at Laboratory No. 3, and D I Blokhintsev's group at Laboratory 'V'. In this section we present only the facts and documents that had been unknown until now and that refer to Landau's work on the theoretical justification of the H-bomb.

The first lengthy discussion of the status of work on RDS-6s and RDS-6t took place at KB-11 on 1 – 8 February 1951 at a session of the Learned Council on issues encountered at KB-11. Present at this meeting were I V Kurchatov, N I Pavlov, I E Tamm, A D Sakharov, K I Shchelkin, Yu B Khariton, Ya B Zel'dovich, G N Flerov, V I Alferov, and M G Meshcheryakov (he did not take part in RDS-6t issues) [70]. The decision of the Council concerning RDS-6t stated:

"2. Issues relating to RDS-6t.

Having heard a communication from Cde. Zel'dovich Ya B and gotten acquainted with the materials attached (reports on the work of Landau and KB-11), the Council points out the following:

Work conducted in 1950 revealed the complexities of the theoretical analysis of the process in the tube that were much harder than expected. New physical factors were discovered: the transfer of part of the reaction energy to electrons in the process of deceleration of the primary reaction products; the large free path and appreciably high probability of reaction of deuterons that gain energy in collisions with 14-MeV neutrons; the predominant role of energy transfer by fast particles (14-MeV neutrons and protons), which may lead to the reaction propagating without producing the shock wave in deuterium.

Calculations of the potentials of the regime that Landau is to complete by 1 July 1951, will inevitably be of an approximate nature and it may happen that no unambiguous conclusion on the possibility or impossibility of burning pure deuterium would be drawn from these calculations.

The Council notes that the preliminary design evaluation carried out at the Institute for Physical Problems revealed great technical problems involved in the implementation of a realistically designed product (use of hydrogen temperatures, creation of a rigid structure with exceptionally thin walls). Whether such a structure can be built depends to a great extent on the results of calculations which are expected to point to the maximum admissible wall thickness and other physical requirements to the system.

Theoretical calculations are based on experimental data; mostly data published in foreign journals are used. Experiments in accordance with the thematic program of the project are needed for determining certain quantities that are lacking, as well as for checking and improving the accuracy of the published data; it is in particular necessary to investigate the secondary processes ($D + He^3$, $D + T$) in the range of high energies and free paths of fast protons and neutrons generated in these processes.

In addition to establishing the conditions required for the propagation of the reaction in deuterium, what is needed for the ultimate decision on creation of the RDS-6t amounts to finding the method of initiating the reaction in deuterium through an explosion of a product with heavy material and an intermediate detonator — a mixture of deuterium and tritium.

As long as the question about the existence of the regime remains unanswered, both the setting up of the study of initiation and the design work on RDS-6t involve certain technical risks, since a definite negative answer concerning the regime would devalue the entire effort.

The Council is of the opinion that it would be expedient to run this technical risk since, in the case of a favorable outcome, early investigation of initiation would shorten the development time of RDS-6t.

Research into initiation would be equally necessary if the results of theoretical calculations on the regime are ambiguous and an experimental search for a solution is required.

Initiation calculations would provide an approximate evaluation of the required amount of heavy fuel and tritium.

The Council believes that, in light of the possibility in principle under favorable conditions, a natural isotope — deuterium — could be used in RDS-6t, which makes it necessary to substantially intensify the effort of creating RDS-6t.

Decision

1. Approve the plan of theoretical works of KB-11 on the RDS-6t problem.

2. Approve the thematic list of works covering nuclear measurements (see Appendix No...) required for RDS-6t. Propose to KB-11 (Khariton is empowered responsible, with

the participation of Landau, Meshcheryakov, and Zel'dovich) to finalize the sequence of measurements, dates, and the necessary accuracy of measurements for each job and submit the plan of nuclear jobs on the RDS-6t problem by 31 March 1951.

3. Approve the plan of research works at the Institute for Physical Problems in accordance with the proposal of Cdes. I V Kurchatov, Yu B Khariton, and Ya B Zel'dovich.

4. Consider it desirable that KB-11 conduct experimental and development works on the issues of initiation and general layout of the RDS-6t product. The plan of experimental work at KB-11 must be submitted by 1 May 1951.

5. Consider it necessary to form a second group of physics theorists and charge it with work on the theory of the RDS-6t gadget in parallel with Landau's group. The group should be headed by Fock and Kolmogorov, with Ambartsumyan attracted as expert consultant.

6. Convene a meeting of the Council at the end of February to hear Landau's report, ensuring participation of Blokhintsev, Bogoliubov, Vladimirskii, Pomeranchuk, and Khristianovich. Landau is requested to present his report in writing by February 1, 1951.

7. Agree with the opinion of Chief Designer Khariton on the need for the Deputy Chief Designer for RDS-6t Zel'dovich to shift the focus of his effort until 1 July 1951 to Moscow, to Landau's group at the Institute for Physical Problems.''

Author's note: *Ambartsumyan — Ar(menian)SSR AS Academician V A Ambartsumyan*; *the number of the appendix in item 2 is missing*.

Having emphasized the complexity of the problem, the Council thus accentuated the need to bring the computation stage to a halt and start organizing the measurements of nuclear constants of the basic reactions.

Ya B Zel'dovich presented a detailed description of the status of work and the necessary measures concerning RDS-6t design (Appendix No. 8 to the decision of the Council, in handwritten form); it will be published in full in the near future in the collected volume, *Atomic Project*. In view of this we shall give only those excerpts from this report by Ya B Zel'dovich that are relevant to characterizing the activities of Landau's group on RDS-6t:

''The main point is the possibility of implementing the regime in liquid deuterium in a tube of unrestricted length. [...]

The issue of the possibility of implementing the regime is being studied by Landau's group in collaboration with the mathematics groups of Meiman (Institute for Physical Problems), Semendyaev (Mathematical Institute of the Academy of Sciences), and Kantorovich (Leningrad Division of the Mathematical Institute of the Academy of Sciences).

At the moment, calculations of auxiliary quantities have been completed: free paths of neutrons, protons, and deuterons. These quantities determine the distance from the point of reaction at which energy is released. Knowledge of free paths makes it possible to calculate energy losses caused by particles escaping through the lateral surface of the tube. The calculation of the amount of deuterium flying sideways after releasing energy in it is nearing completion. All quantities needed for the mathematical formulation of the main problem on the properties and existence of the regime of propagation of the reaction along a long-length charge have thus been prepared. In accordance with the resolution of the Council of Ministers this problem must be solved by 1 July. Judging by the way the work is progressing, Landau's group will meet the deadline.

It should be remembered, however, that the solution that Landau's group will provide will be approximate by virtue of the method of obtaining the result. Therefore, the correctness of the answer will be verified by just checking if individual mathematical operations are executed impeccably. It is necessary to verify the correctness and evaluate the accuracy of physical simplifications and assumptions made in the course of calculations. It cannot be excluded that insufficient accuracy of calculations would not permit drawing unambiguous conclusions on the feasibility of the process. [...]

We therefore consider that the following three measures should be implemented now:

1. Creation of a second group of physics theorists (involving some mathematicians) which would deal with the issue of the regime of reaction propagation, using to the full the results obtained earlier by the groups at the Institute of Chemical Physics and KB-11, and by Landau's group.

We can expect that the physicists in this group would conduct a comprehensive expert assessment and verification of the results obtained earlier and would work out new approximate methods for considering the problem. If essentially different approximate approaches yield the same results, the confidence in their correctness would be considerably greater. The involvement of a new group of physicists may also lead to their generating new ideas and suggestions regarding the utilization of light elements.

In our opinion, the second group of physicists should be led by Academician Fock and Ambartsumyan, relieving them of all other duties for an appropriate period of time.

2. Accelerated development of electronic computers and mathematical preparation of the problem of the regime so it can be forwarded to digital computations. [...]

3. Intensification of contacts between KB-11 and Landau's group, taking the view that Zel'dovich's main target for 1951 should be his personal participation in the work of Landau's group, as well as participation in promoting the work of the second group of physicists. In the matter of the second issue — initiation of the regime — so far the work has only been conducted at KB-11 (Landau's group will join the study of this subject only after completing their work on the theory of the regime). [...]

Four aspects can be outlined regarding the initiation issue:

1. Design (conceptional) elaboration of the heavy charge suitable for initiation. [...]

2. Improved calculation of external ignition in deuterium–tritium mixtures. [...]

3. Calculation of reaching the regime in the deuterium charge by the action of ignited deuterium–tritium mixture. Only this calculation will make it possible to determine the amount of tritium required to start the regime in deuterium (assuming that this regime is possible). In compliance with a resolution of the Council of Ministers, this calculation is the responsibility of Landau's group after it completes regime calculations.

4. Final design of the entire object utilizing the results provided by all research projects listed above. This work is being done now by the Institute for Physical Problems and KB-11. The Institute for Physical Problems is now conducting and will continue to conduct the cryogenic and technological study of the tube. It should be mentioned that any work concerning initiation can be brought to completion only when a solution to the regime issue is available; [...].''

The reverse side of this document bears the mark: "executed by hand in a single copy, on nine sheets, by Frank-Kamenetskii."

We see that Ya B Zel'dovich in his report at a meeting of the KB-11 Council emphasized the first-priority importance of calculating the regime of stationary thermonuclear reaction in liquid deuterium, on which Landau's group was working.

To better understand the problems that surfaced in the work on RDS-6t gadget, we quote here a brief description of its main principles, for which purpose we make use of a memorandum prepared by Yu B Khariton and Ya B Zel'dovich, "On the current status and plan of works for RDS-6t on 31.01.1953" [71] which states, among other things:

"RDS-6t is understood as a device operating on the principle of *detonation* of liquid *deuterium*, which initiates *thermonuclear* reactions. The reaction with *deuterium produces tritium and helium-3* which enter a secondary reaction themselves and generate fast particles — *neutrons and protons*. A distinctive feature of RDS-6t is that reactions proceed at a very high temperature, on the order of 50–100 keV, at which matter is not in equilibrium with radiation. Bremsstrahlung radiation emitted by electrons is the main channel for heat loss. Further on, this radiation is scattered by electrons, which additionally removes heat from them. This last process is known as Comptonization. The propagation of the reaction through the deuterium charge proceeds via compression and shock wave heating and also via energy transfer by fast particles. The structural implementation of RDS-6t can be either as a cylindrical tube or as a spherical system. The radius of the spherical system cannot be too large, as a large radius means that radiation stays inside the sphere for too long time, thus greatly increasing losses to Comptonization and leading to damping of the reaction. Increasing the length of the tube does not result in this complication. Consequently, if stationary propagation of a *thermonuclear* reaction is proved possible in a cylindrical tube, it would in principle be possible to run the burning of *deuterium* in any amounts.

To start the reaction, a high temperature is needed and this can be achieved by an *atomic explosion* of heavy *fuel*."

The authors of the memorandum then write:

"In order to establish the qualitative pattern of motion, and to work out the methodology of hydrodynamical calculations, a decision was reached at the beginning of 1951 to conduct calculations for a simplified gas dynamics problem. The idealization consisted in the fact that energy transfer by fast particles and quanta was ignored, the local rate of energy release was assumed proportional to the pressure, and the heating of matter ahead of the wave front was ignored. The idealized problem was being solved by L D Landau's group and N S Meiman's bureau at the Institute for Physical Problems. Landau worked on a nonstationary method of solving the problem. However, this work was left unfinished as L D Landau's group and N S Meiman's bureau were reoriented to RDS-6s calculations. Other methods for solving the idealized problem were being worked on by the group of Keldysh and Dorodnitsyn at MIAN."

We can have an idea of the type of computational and theoretical works on clarifying the feasibility of detonation of liquid deuterium, carried out by Landau's group in 1950–1951, from his report on the current status of work on 1 October 1951; it was sent to the FMD on 15 October 1951 and stated the following[72]:

"Report on the current status of work on 1 October 1951.

I. Work on the Compton effect

In this area, the target was to find the main characteristics of single events of Compton scattering of photons in a relativistic electron gas, which would subsequently constitute the foundation for evaluating the Compton effect in various concrete geometric conditions in the object.

We introduce as the basic quantities characterizing the act of a photon scattering: 1) the mean free path of a photon with respect to collisions with electrons; 2) the mean energy transfer from electrons to the photon; 3) the mean square of energy transfer to characterize the width of distribution over energies, and 4) the mean momentum transfer to characterize the mean change in photon direction.

Theoretical formulas were devised for all these quantities and numerical calculations were then carried out using them in L V Kantorovich's and N S Meiman's bureaus. Detailed tables were compiled for all quantities as functions of the photon initial energy and electron gas temperature.

The knowledge of energy and direction distribution functions for photons may also be important for specific applications. In collaboration with Gandel'man, we devised exact formulas that make it possible to generate exact distribution functions by single numerical integration. These formulas are extremely unwieldy and bulky, so that it would be useful to have simple interpolation formulas. We proposed such a formula for the photon distribution function over energies and for coefficients in it.

L D Landau 2 October 1951."

The space allotted to this article does not make it possible to reproduce here the text of the report "On the possibility of detonating deuterium in the tube" written by L D Landau, E M Lifshitz, I M Khalatnikov, and S P D'yakov on 1 February 1951 [73]. As we read on the reverse of the last page of the report: "written by hand in a single copy from the draft, pp. 49–64 of the working notebook No. 502 of E M Lifshitz. Exec. E Lifshitz. Rewritten by S D'yakov. 1.II.51. The draft sealed into a separate shell. E Lifshitz." In addition, the page bears the signatures of those who read this report: "read by N Bogoliubov 19.02.1951, I Kurchatov 19.02.51, I Pomeranchuk 22.02.51."

A representative meeting devoted to the RDS-6t problem took place on 8–9 January 1952 at the FMD, which involved the main participants of the computational investigation (names given as in the protocol): Yu B Khariton, Ya B Zel'dovich, I E Tamm, L D Landau, M V Keldysh, I Ya Pomeranchuk, I M Gel'fand, A A Dorodnitsyn, K A Semendyaev, D I Blokhintsev, I M Khalatnikov, E M Lifshitz, N S Meiman, and others [74]. The protocol (handwritten) was compiled by G Gandel'man but not signed by anyone; it only contained the statement of the results of calculations on RDS-6t, carried out by different research groups. Reports on the status of computational studies on RDS-6t were presented by Ya B Zel'dovich, I E Tamm, L D Landau, N S Meiman, N A Dmitriev (ICP), K A Semendyaev, and others. The statement section of the protocol pointed to the following apropos of the issues broached by N S Meiman and L D Landau in their communications:

"The communication of N S Meiman (Landau's group). The method of numerical integration of the nonstationary dynamic problem (for the one-dimensional case).

I M Khalatnikov and N S Meiman developed a stable method of computations making it possible to compute with large time steps. A stable difference scheme, convenient for computing, was thought up.

The report by Academician Landau emphasized that the situation is much more complicated in the spatially two-dimensional case. Computations will be carried out in toroidal coordinates, in a manner that allows different spatial steps of computation in two directions of this coordinate system. Completely developed at present is the method of computations for one-dimensional problems and much has been done for preparing a method of computations for two-dimensional problems.''

Landau presented abstracts of the following reports for this meeting [75]:

1. L D Landau, E M Lifshitz: ''On reflection of weak discontinuity from the sonic line'' (mb. 44sd).

2. L D Landau, E M Lifshitz, N S Meiman, I M Khalatnikov, S P D'yakov: ''On the solution to the two-dimensional nonstationary gas dynamics problem'' (mb. 45sd).

3. L D Landau, E M Lifshitz, I M Khalatnikov: ''Integration of hydrodynamical equations by the grid method'' (mb. 46sd).

Abstracts of these reports are reproduced in the appendices.

(*Author's comment*: *here and further on, italics mark words written into the document by hand.*)

To clarify the situation with the work on the RDS-6t gadget, A P Zavenyagin signed the following order [76] on 6 April 1953:

''For checking the state of affairs with computational, theoretical, and experimental work on the RDS-6t product carried out at KB-11 and the Mathematical Institute of the USSR Academy of Sciences, I order:

1. Appoint a commission composed of Cdes. Blokhintsev D I (chairman), Bogoliubov N N, Keldysh M V, Landau L D, Meshcheryakov M G, Pomeranchuk I Ya, Tamm I E.

Cdes. Zel'dovich Ya B and Semendyaev K A will take part in the work of the commission

2. Entrust the above commission with considering, before 25 April 1953, the results obtained at KB-11 and the Mathematical Institute of the USSR Academy of Sciences on the RDS-6t product and to submit to the USSR Council of Ministers PGU an evaluation of the current status of this work and a plan of further computational, theoretical and experimental research on the above-indicated product in 1953.''

This executive order reveals that, first, the best physicists and mathematicians were invited for the expert evaluation of RDS-6t-related computations in order to reach certainty on the prospects of the project. Second, the instruction to the commission to prepare additions to the plan of research indicated that the management and scientific leadership were of the opinion that the work on RDS-6t should be continued; indeed, the commission was ordered to prepare the plan of research.

The conclusions reached by the commission chaired by D I Blokhintsev on 6 May 1953 and presented in compliance with this executive order read [77]:

''In accordance with Cde. A P Zavenyagin's order No. 135ts/sd of 6.04.1953, the commission consisting of Cdes. Blokhintsev D I (chairman), Bogoliubov N N, Keldysh M V, Landau L D, Meshcheryakov M G, Pomeranchuk I Ya, and Tamm I E, with the participation of Cdes. Zel'dovich Ya B and Semendyaev K A, considered on 6 May 1953 the reports of *KB-11* Nos 753-sd and 763-sd compiled on the basis of the work of the group of Cdes. Zel'dovich Ya B and Semendyaev K A, and heard reports on the status of work in other groups (MIAN, Laboratory 'V', TTL, and IPP).

The commission gives the general assessment of the state of work on the *RDS-6t* product using as a basis the above consideration, and formulates recommendations on the subsequent plan of works and the plan of measures required to complete this program.

RDS-6t is understood as a gadget operating on the principle of *detonation* of liquid *deuterium*, which initiates *thermonuclear* reactions.

The propagation of the reaction through the *deuterium charge* proceeds via compression and heating by the *shock* wave and via energy transfer by fast particles. The structural implementation of *RDS-6t* can be either as a cylindrical tube or as a spherical system. The radius of the spherical system cannot be too large, as a large radius means that radiation stays inside the sphere for too long time, thus greatly increasing losses to Comptonization and leading to damping of the reaction. Increasing the length of the tube does not result in this complication. Consequently, if stationary propagation of the *thermonuclear* reaction is proved possible in a cylindrical tube, it would in principle be possible to run the burning of *deuterium* in any amounts.''

Author's comment: *This last paragraph was reproduced to demonstrate that the members of the commission were acquainted with the memorandum of Yu B Khariton and Ya B Zel'dovich classified as* '*top secret — special dossier*' [71].

The full text of the final report of the commission will supposedly be published in Vol. 3 of the book *Atomic Project* and consequently we only quote here several excerpts, namely:

''[...] 1. The studies carried out in the last two years and especially those conducted by the groups of Cdes. Zel'dovich Ya B and Semendyaev K A, made our knowledge of the *detonation* process in a cylindrical *charge* of liquid *deuterium* considerably more profound.

In this work it was possible to study the motion of matter under *detonation* of a cylindrical *charge*, and to determine the profile of the curved shock wave, density distribution and pressure distribution in the reaction zone, and the motion of matter in flying apart.

This picture of motion was first obtained for the phase of compression of cold *deuterium* by the shock wave, and then for the real case when *deuterium* ahead of the shockwave front was heated by impinging fast particles.

The calculation method is approximate and introduces a certain arbitrariness into finding the shock wave form and some other quantities, since the rate of energy release required for sustaining the calculated temperature field, pressure, etc. emerges only when calculations are completed and the problem can be solved for the necessary distribution of energy release only by successive attempts.

Detailed calculations were carried out of the progress of reactions, of energy release and heat loss taking into account energy transfer by particles and through the Compton effect, using the distributions of density, pressure, temperature, and flow rate.

For a number of scenarios with different radii and temperatures, energy balance in the entire reaction zone was calculated. [...]

2. In view of the extreme complexity and diversity of physical processes that govern the *detonation* of liquid *deuterium*, it is impossible to take into account all the factors affecting it. Consequently, a realistic accuracy better than 25 – 30% cannot be expected, even from a calculation ameliorated to the maximum degree.

It is thus clear that providing an affirmative answer to the question about the possibility of *detonation* of liquid *deuterium*, and reliably finalizing the cylinder radius required for the propagation of *detonation* would only be possible if the improved calculation shows that *detonation* remains possible, and the range of radii necessary for its initiation remains sufficiently wide, even when input physical data are changed for the worse by 20 – 30%.

3. Even though approximate calculations carried out so far have failed to provide a definitive negative or positive reply to the question of whether *detonation* is possible or not, insufficient accuracy remains such that the option of *detonation* being possible cannot be ruled out completely, even in a rather broad range of cylinder radii.

4. In view of the exceptional complexity of the problem of *detonation* of liquid *deuterium*, its more accurate investigation would call for a long time and unavoidably [high] number of physicists and mathematicians from among the top in the profession.

It is rather difficult to specify the deadlines for these research programs at this moment, as the methods of calculation are not yet sufficiently advanced and the volume of work is enormous. [...]

The following issues need to be resolved for arriving at a solution to the *RDS-6t* problem:

1. To clarify if detonation-induced burning of long cylindrical *charges* of liquid *deuterium* is feasible.

2. To calculate energy release in a spherical *charge* of liquid *deuterium* initiated by a *charge of TD*.

3. To develop the theory of initiation of *detonation* in a cylindrical charge and to determine the required amount of tritium.

4. To investigate the possibility of reducing the amount of tritium required to ignite a cylindrical or spherical *charge* by compressing *deuterium* and *TD* (proposal by Blokhintsev – Gandel'man).

5. To design the structure and perform the calculations for products with heavy fuel intended for the primary combustion of a *TD* mixture.

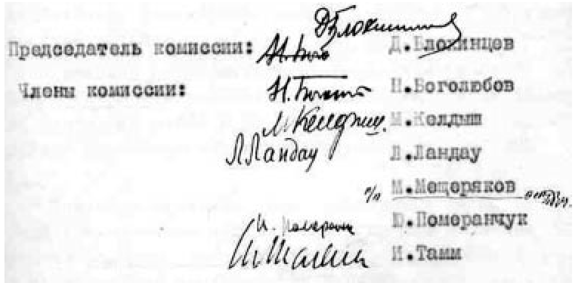
To draw conclusions on the expedience of practical implementation of the RDS-6t product, it is also necessary to study at least approximately certain promising scenarios of *superpowerful* products based on other principles. The commission has not included the relevant aspects in its deliberations.

Among the five issues above, the commission considers it advisable to focus efforts on items 1, 2, and 4 (possibility of *detonation* in a cylindrical charge, spherical systems, and compression of systems) as being more principally important.

The necessity for a detailed analysis of issues 3 and 5, as well as detailed design work on the RDS-6t product, has to be decided depending on the final results of the work on issues 1, 2, and 4."

Author's comment: *TD — tritium – deuterium*.

The commission formulated its suggestions to the plan of works on RDS-6t gadget in which the following organizations were to participate: KB-11 (work headed by Ya B Zel'dovich), MIAN (M V Keldysh), TTL (I Ya Pomeranchuk), and Laboratory 'V' (D I Blokhintsev). The findings were unanimously signed by all members of the commission:


Председатель комиссии: Д. Блохинцев
Члены комиссии: Н. Боголюбов
М. Келдыш
Л. Ландау
М. Мещеряков
И. Померанчук
И. Тамм

On 29 May 1953, A P Zavenyagin and I V Kurchatov sent L P Beria a memorandum with a draft order [78] based on the final report of D I Blokhintsev's commission. We show here some excerpts from this memorandum:

"In compliance with the USSR Council of Ministers Resolutions No. 827-303ts/sd of 25.02.1950 and No. 1552-774ts/sd of 9.05.1951, KB-11 and related organizations (the Mathematical Institute, the Thermo-Technical Laboratory, the Institute for Physical Problems of the USSR Academy of Sciences, and Laboratory 'V' of the First Main Directorate) are working on the problem of *thermonuclear explosion* of liquid *deuterium* (*RDS-6t* product).

To evaluate the general state of work on the RDS-6t product and prospects for the development of the product, the First Main Directorate of the USSR Council of Ministers set up a commission composed of Cdes. Blokhintsev (chair), Bogoliubov, Keldysh, Landau, Meshcheryakov, Pomeranchuk, and Tamm.

The Commission looked into the status of work on the RDS-6t product in a number of organizations, formulated the summary of the general status of work in the field, and outlined a plan of further computational and theoretical works on project RDS-6t.

The Commission noted that the research conducted in the last two years made our knowledge of the process of *detonation* of liquid *deuterium* considerably more profound.

However, in view of the exceptional complexity of physical processes that determine the course of *detonation* of liquid *deuterium* and because the calculations conducted are insufficiently accurate, it is not possible at the moment to give a definitive answer to the question concerning a feasibility of *detonation* of liquid *deuterium*.

At the same time, it cannot be ruled out that a more accurate investigation of the RDS-6t problem may lead to an affirmative answer to the question."

The authors of the memorandum then informed L P Beria of the scientific problems related to RDS-6t that the commission formulated and advanced the following organizational suggestions:

"The solution to these problems should be entrusted with KB-11, the Mathematical Institute of the USSR AS, the Thermo-Technical Laboratory of the USSR Academy of Sciences, and Laboratory 'V' of the First Main Directorate. It would be expedient to charge the Institute for Physical Problems of the USSR Academy of Sciences with developing the structure of the cylindrical *charge*, while Cde. Landau's group, now engaged completely with the work on the RDS-6s product, should be released from computational and theoretical works on the RDS-6t product."

Two weeks later, on 10 June 1953, B L Vannikov sent L P Beria a letter in which he stated [79]:

"Having considered according to your assignment the suggestions of the First Main Directorate (Cdes. Zavenyagin, Kurchatov) of 29 May of this year on the work concerning the RDS-6t product, as well as the evaluation made by the commission of specialists chaired by Cde. Blokhintsev, I have this to report:

1. In accordance with the Resolution of the USSR Council of Ministers of 28 February 1950, Cde. Landau's group at the Institute for Physical Problems conducted in 1950–1951 computational and theoretical works on clarifying whether the detonation of a cylindrical charge of liquid *deuterium* is feasible or not.

Cde. Landau approached the calculations under the assumption that detonation of *deuterium* can be achieved purely by nuclear processes. However, the ultimate result was negative: *thermonuclear reaction* in the RDS-6t product under this assumption is impossible.

In this connection, the necessity arose to take into account, when considering the process of *deuterium* burning, the effect of the shock wave on sustaining the nuclear reaction.

As Cde. Landau was subsequently charged with work on the *RDS-6s* product, he was relieved of computational and theoretical work on the *RDS-6t* product."

Then B L Vannikov formulated a number of organizational proposals concerning RDS-6t, among them item 4:

"4. Cde. Landau's group needs to be relieved of assignments for the *RDS-6t* product that were theirs by virtue of the governmental resolution of 26 February 1950, in view of Cde. Landau being busy with computational and theoretical work for the product of the *RDS-6s* type."

We now know that work on the 'tube' version of the H-bomb was discontinued by a decision of the Ministry of Middle Machine Building in 1954.

B L Vannikov pointed out in his memorandum of 10 June 1952 that "Cde. Landau and his group have been engaged since December 1951 in work on product *RDS-6* and continue to be fully engaged in this work" [79]. Task orders to Landau's group were set at the governmental level by the USSR Council of Ministers Resolution No. 5373-2333ts/sd of 29 December 1951 [80]:

"2. Taking into account that the work on creation of the *RDS-6s* product advanced much further than that on the *RDS-6t* product, charge the First Main Directorate of the USSR Council of Ministers (Cdes. Vannikov, Zavenyagin), Laboratory of Measurement Instruments (Cde. Kurchatov), KB-11 (Cdes. Aleksandrov, Khariton, Shchelkin) with concentrating the main contingent of physicists, mathematicians, and designers in 1952 on accelerating progress with the *RDS-6s* product. In this connection:

a) involve Cdes. Landau, Zel'dovich, Keldysh, Blokhintsev, and Kolmogorov in the work on *RDS-6s*;

b) charge Cdes. Landau, Zel'dovich, Keldysh, Blokhintsev, and Kolmogorov to get acquainted with theoretical and computational work on *RDS-6s* and submit to the First Main Directorate in January 1952 their conclusions on the status of work;

c) charge Cdes. Vannikov, Zavenyagin, Pavlov, Kurchatov, and Khariton with assessing at the Scientific and Technical Council on the issues of KB-11 the expert evaluation submitted by Cdes. Landau, Zel'dovich, Keldysh, Blokhintsev, and Kolmogorov and outlining and approving before 15 February 1952 the measures required to speed up work on creating *RDS-6s*. [...]

4. Partially change the USSR Council of Ministers Resolution No. 827-303ts/sd of 26 February 1950 so as to postpone the deadline for computational and theoretical work on clarifying if implementing the *RDS-6t* product is possible (responsibility of the Institute for Physical Problems of the USSR Academy of Sciences, Cdes. Aleksandrov and Landau) to 1 March 1953."

Landau started working on the commission at the beginning of January 1952. The commission consisted of Ya B Zel'dovich, M V Keldysh, D I Blokhintsev, and A N Kolmogorov and was formed in accordance with the above resolution of the USSR Council of Ministers. On 30 January 1952, Ya B Zel'dovich as chairman sent B L Vannikov the conclusions drawn by the commission, with his personal comments [81]:

"To Cde. Vannikov B L

In accordance with the governmental Resolution No. 5373-2333ts/sd of 29.12.1951, a commission composed of Landau L D, Keldysh M V, Kolmogorov A N, Blokhintsev D I, and Zel'dovich Ya B, with Tamm I E and Sakharov A D participating, considered the status of theoretical work on RDS6S.

The commission concluded that the design of RDS6S makes possible the implementation of a thermonuclear explosion using tritium and deuterium. The commission accepts as substantiated the conclusions of A D Sakharov and I E Tamm that the product with the charge of [...] tritium would produce an explosion with a total TNT equivalent from 700,000 to 1,400,000 tonnes.

In order to improve the calculations carried out for exploding RDS6S and for preparing the explosion of the test product, the commission assumes the following as necessary:

1. Intensify the work on calculations dealing with the process of explosion and with energy release by the multilayer charge, including calculations for the test explosion with [...] of tritium planned for 1953. To complete the calculations, involve Landau's group in the work in parallel with Tikhonov's group.

2. Intensify the experimental work on mixing. Involve new experimental groups in executing this work. Conduct work on mixing with the participation of Kolmogorov and Landau as consultants.

3. Conduct work on selecting the design version of the central core charge using the compound charge of plutonium and uranium-235. Charge the work on selecting a design version to Zel'dovich's group.

4. Continue the planned measurements of nuclear constants, including reactions with lithium-6.

5. Continue experimental and theoretical studies of the compression process as foreseen by the plan, and among other things, find the causes of the currently observed discrepancy (of about 15%) between the results of calculations and observations concerning the flight trajectory of the shell of RDS6S.

To recapitulate: In accordance with the decision of the Government it is suggested to include Cdes. Landau, Kolmogorov, and Zel'dovich in the program of work on RDS6S. Including Cdes. Keldysh and Blokhintsev in the work on RDS6S is currently not considered advisable.

I attach detailed findings of the commission on 6 sheets.

Chairman of the commission Zel'dovich."

Author's comment: *RDS6S — as in the document*.

After reading the conclusions of the commission on RDS-6s given below, we will be able to comment on these two historical documents [82]:

"Conclusions of the commission on the status of computational and theoretical work on the RDS6S product.

1. In 1948–1951, the group of I E Tamm and A D Sakharov proposed and investigated a new principle of developing a hydrogen product — a multilayer charge (MC), clarified the role of the main physical factors and developed the conceptional scheme of calculations required for multilayer charges.

2. The measurements of elementary nuclear constants (Frank, Flerov, Kondratiev) and neutron experiments with a model MC (Frank's group and Zysin's group) provided the basic characteristics necessary for calculating the principal chain of physical processes that take place in an MC.

3. An improved method of calculations in neutron problems was developed (Yu A Romanov). [...]

6. The functioning of an MC was simulated by integrating a set of equations of motion, heat conduction, thermonuclear reaction, diffusion, and multiplication of neutrons (Tikhonov's bureau). The results of these simulations describe in the first approximation the peculiarities of processes occurring during the explosion of an MC and yield, in the first approximation, the amount of energy released in the explosion.

The Commission accepts as substantiated the estimate submitted by Sakharov and Tamm's group, based on the work they did, that the product would release an amount of energy with a total TNT equivalent estimated as 700,000 to 1,400,000 tonnes. The following factors contribute to this broad range of estimates of the explosion energy:

1. Experimental work on mixing has not progressed well enough; the accuracy of these experiments is insufficient; the curve of concentration distribution in the mixing layer has not been measured; no experiments were run on mixing in a light layer sandwiched between two heavy layers; no data are available on the viscosity effect.

2. Complete computational stability has not been achieved in calculations of the effect of the MC, which limits the accuracy of computing the energy release and makes it impossible to judge the reliability of peculiar features of the curves obtained; the theoretical analysis of stability and methods of averaging the differential equations of the process has not been completed.

3. Total quantitative agreement between calculations and experiments on MC compression has not been achieved.

4. The achieved accuracy in measuring nuclear constants and the accuracy of modelled neutron experiments is such that it limits the accuracy of computations for energy release. The Commission deems it desirable to convene a meeting of groups of experimentalists who work on obtaining nuclear constants for the RDS6S problem, in order to exchange experience, as well as bring into agreement the results and harmonize plans.

Task orders in the near future for the work on RDS6S, in addition to the work on the basic structure, should be:

1. Completing calculation of the test explosion.

2. Running calculations for different design versions of the inner charge composed of active heavy materials.

3. Calculating different versions of structures with layers of different thicknesses.

To improve all these computation procedures it is necessary to further improve the accuracy of nuclear constants (such as $Li^6 + n$) and model neutron experiments.

Suggested measures.

1. Charge Cdes. Konstantinov B P (LPTI) and Strelkov S P (TsAGI) with conducting experimental studies on mixing liquids of different densities.

2. Charge L D Landau's group and N S Meiman's bureau (IPP) with conducting in 1952 calculations on the effects of the MC in parallel with Tikhonov's bureau. The Commission considers it desirable that Landau's group and Meiman's bureau begin working on the project on 1 February 1952.

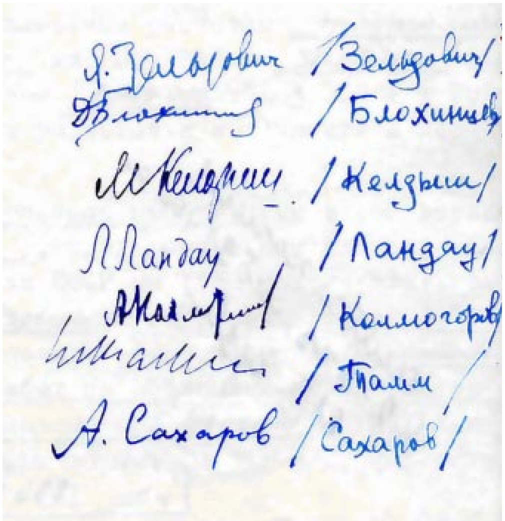
To have the effort properly supported, consider it necessary to relieve Landau's group and Meiman's bureau in 1952 of the work on RDS6T assigned to them earlier, and strengthen Meiman's bureau with 3 specialists with candidate of sciences degrees.

3. Charge Zel'dovich's group (Zababakhin, Negin) with conducting approximate calculations for the selection of the design version of the central charge.

4. Strengthen Tikhonov's group by transferring Cde. Samarskii (full-time occupation) to Tikhonov's group, attaching to group 3 [university] graduates and increasing by 12 the allowed number of employed engineers and laboratory assistants.

5. Charge Cde. Khariton with assessing if it is possible to arrange experiments on mixing under conditions of explosion of conventional explosives and outline a program of possible experiments by 1 March 1952."

These conclusions were signed unanimously by all members of the commission, as well as by I E Tamm and A D Sakharov also enlisted in a commission's work, although no signatures were dated, as we see in the facsimile copy shown here.



It is clear from the above-reproduced conclusions of the commission of highest-class specialists that the creation of an H-bomb faced a considerable number of theoretical and experimental problems, as late as only a year and a half before the pilot product was exploded. Notice that the decision of 1–9 February 1951 taken by the NTS on issues of KB-11 stated [71]:

"Calculations met with great difficulties of a mathematical and computational nature. The first calculation of energy released by the explosion of one design version took six months of work by Cde. Tikhonov's bureau. The calculation of compression for one scenario of dimensions of a multilayer charge took 4 to 5 months of work by Cde. Semendyaev's bureau."

For this reason, and also because of the exceptional complexity of processes in RDS, several groups of physicists and mathematicians were involved. For the same reason, a request kept reappearing for adding new members to the staff of research groups working on RDS, including mathematicians.

The above recommendations of the commission were confirmed at a meeting at the FMD, and the management of the FMD reported on the results of this meeting to L P Beria in a letter of 27 February 1952 which stated [83]:

"In compliance with the USSR Council of Ministers Resolution No. 5373-2333ts/sd of 29 December 1951, a commission composed of Cdes. Zel'dovich, Landau, Keldysh, Blokhintsev, and Kolmogorov considered the theoretical and computational work on *RDS-6s*, carried out at *KB-11* and in the mathematical bureau of Cde. Tikhonov. The conclusions of the commission were discussed at a meeting at the First Main Directorate that involved Cdes. B L Vannikov, A P Zavenyagin, Pavlov, Khariton, Zernov, Aleksandrov, Landau, Keldysh, and Zel'dovich.

The commission concluded that the design of *RDS-6s* is adequate for implementing a *thermonuclear explosion* with the use of *tritium*.

According to preliminary computations, the *TNT* equivalent of the *explosion* of a multilayer *charge* with [...] *tritium* should equal *1,050,000* tonnes ±35% (the figure 35% reflects inaccuracies in the computations and inaccuracy in measurements of nuclear constants).

The commission recognized it necessary to add to the work on *RDS-6s* foreseen by the plan approved by the USSR Council of Ministers for 1952 some efforts intensifying the computational work on the process of *explosion* and energy release in *RDS-6s* and on the *prototype* product intended for *testing* in *1953*, as well as the work on studying *mixing* processes generated by the *explosion* of the *RDS-6s* product. [...]

The following measures are considered in order to intensify the computational and theoretical efforts for the *RDS-6s* product:

1. Involve Landau's group at the Institute for Physical Problems of the USSR Academy of Sciences in calculations of the process of *explosion of RDS-6s*.

2. Assign the conduction of the experimental work on studying the *mixing* processes in the *multilayer charge* on orders by KB-11 to Cdes. Kikoin, Millionshchikov, and Sobolev at the Laboratory of Measurement Instruments of the USSR Academy of Sciences, and also to DSc researchers Folmer and Rikhter at NII-9.

Involve Cdes. Kolmogorov and Landau as consultants in the theoretical work on *mixing*. [...]

3. Convene a meeting in March 1952 covering the results and methods of measuring nuclear constants required for the calculations on the *RDS-6S* products.

The Resolution of the USSR Council of Ministers of 29 December 1951 foresees the involvement of Cdes. Landau, Zel'dovich, Keldysh, Blokhintsev, and Kolmogorov in the work on *RDS-6S*.

The present draft order for conducting the work on *RDS-6S* additionally assigns it to Cdes. Landau, Zel'dovich, and Kolmogorov.

The computational and theoretical groups of Cdes. Blokhintsev and Keldysh will not be instructed to join, for the following reasons:

1. The computational and theoretical work on neutron processes, in which Cde. Blokhintsev's group is highly specialized, was conducted in *KB-11* at a sufficiently high level and does not require further strengthening.

2. Mathematical computations conducted by Cde. Tikhonov's bureau will also be carried out by Cde. Landau's group involved in the work on *explosion* processes. Formation of a third parallel group headed by Cde. Keldysh for computations relevant to the *RDS-6S* product is not considered advisable.

As Cde. Landau's group was relieved of the work on RDS-6T in 1952, we instructed KB-11 (Cdes. Khariton and Zel'dovich) to review and improve the plan of research on RDS-6T, so that it uses to the maximum the computational and theoretical groups of Cdes. Blokhintsev and Keldysh.

We submit for your consideration the conclusions of the commission on the *RDS-6S* product and a draft order of the USSR Council of Ministers, with a request to have it approved."

On 13 April 1952, A P Aleksandrov and L D Landau sent A P Zavenyagin the following memorandum on the status of work on RDS-6 [84]:

"On the instructions of Cde. Pavlov, here is our report on the status of work on the sloika (or Layer Cake).

Author's note: *sloika stands for a code word of multilayer charge of an H-bomb*.

Academician L D Landau and his group comprising Prof. E M Lifshitz, CdSc I M Khalatnikov, and CdSc S P D'yakov started their work on 15 March this year. D V Sivukhin is to join this project on 7 April this year.

The time since the work started was devoted to developing the method of solving the problems involved. One of the main difficulties inherent in the problem consisted in the speed of propagation of both particles and heat, so that conventional computational schemes become virtually useless. As an example, at Tikhonov's bureau the process was split in time into 350 steps and nevertheless computational stability has not been achieved. At the moment we are working on a scheme with which it will be possible to compute the process of propagation of particles in a stable manner and go through a smaller number of time steps. The idea of this scheme has already taken shape. At present we have prepared a number of tasks for the mathematical bureau. We plan to complete the development of the principal method in May and then begin computations.

It is essential that the computation bureau be able to join in solving the already prepared assignments, but this needs Your direction because any delay in this matter may slow down the entire program."

This anxiety of A P Aleksandrov and L D Landau regarding the work of the computation bureau had a very real basis, as the security clearance for N S Meiman to the work on RDS-6s was indeed very slow in coming. As a result, the situation forced Landau and Tamm to address L P Beria personally two weeks later about the matter of N S Meiman by writing the following letter — a step that was very unconventional in those times [85]:

"To Comrade BERIA L P

We write to You in view of an unexpected and urgent problem that is having a bearing on completing calculations for the project of multilayer charge.

When plans for these task orders were drawn up it was expected that an essential part of calculations assigned to L D Landau's group would be conducted by the Mathematical Bureau of the Institute for Physical Problems, headed by Meiman N S.

At the moment, the unexpected apprehension has arisen that Meiman will not be given access to this work.

Meiman had organized this bureau at IPP and for nearly five years directed the computations that this bureau carried out both in the matter of efficiency of the conventional product and in the problems of the RDS-6t product.

When solving these problems, Meiman developed new, very efficient methods of mathematical computations, which in the current year need to be applied to computations for the multilayer charge.

In our opinion, refusing access to Meiman as head of the program of computations at the IPP Mathematical Bureau on calculations for the multilayer charge would produce a most harmful effect on the progress of these calculations and would result in very considerable time delays in this work.

L Landau, I. Tamm 3 May 1952.''

In connection with this letter from L Landau and I Tamm, A P Aleksandrov was instructed by N I Pavlov to send to the FMD an ''Information sheet on Head of the Computation Bureau of the Theoretical Physics Department of the Institute for Physical Problems, MEIMAN Nakhim Sanelevich'' which stated [86]:

''Meiman Nakhim Sanelevich — possesses security clearance [...] of 26 November 1946 that corresponds to his position as Head of the Computation Bureau of the Theoretical Physics Department at the Institute for Physical Problems of the USSR Academy of Sciences.

This Computation Bureau was organized on the instructions of Cde. Vannikov B L and was intended to provide mathematical treatment of the results of calculations conducted by Academician Landau L D, who was entrusted with calculating the efficiency of products.

N S Meiman worked at the Institute for Physical Problems pluralistically as head of the Computation Bureau as of 1 March 1947 (his principal employment was at the Institute of Physical Chemistry of the USSR Academy of Sciences) and has been working full-time since 1948.

In 1948, he was approved to work on the topic of ''Calculation of the efficiency of spheres with an infinite shell'' (USSR CM Resolution No. 1137-403ts of 6.1.1948).

In 1949, he was approved to work on the topic of ''Efficiency of objects with a complex layered structure'' (the plan of the Institute approved by Cde. Emel'yanov V S).

In 1950, he was approved to work on the mathematical side of the theme ''Calculation of efficiency of multilayer systems using an improved algorithm'' (research program for the Institute approved by Cde. Emel'yanov V S).

In 1951, he was written into the thematic plan for the Institute as an executor for the topics ''Calculations of efficiency of spheres with a thin shell'' and ''Calculations for Ya B Zel'dovich's case''. The plan was submitted to Cde. Pavlov N I.

In 1952, he was approved to work on the topic ''Calculations for Ya B Zel'dovich's case (the 'tube'), in the plan of the Institute approved by Cde. Pavlov N I.

In 1950, he was awarded a cash bonus (for computations on conventional products) by an Order of the USSR Council of Ministers No. 2108-814s of 16 May for completing a special assignment.

During his work at the Institute Cde. Meiman N S suggested a method of computations that was transferred to, and approved by, other bureaus.

The Computation Bureau headed by Cde. Meiman N S regularly met deadlines on all its assignments and accumulated much experience in the relevant fields. A P Aleksandrov.''

Furthermore, A P Aleksandrov sent a petition letter to the Special Committee with the following request [87]:

''To Comrade BERIA L P

Presenting to You the letter from Cdes. Landau L D and Tamm I E, I add the following information:

In connection with involving Academician Landau in the work on the 'sloika', Cde. Pavlov gave me instructions for the necessity of additional security re-vetting of the staff of the computation bureau despite the fact that all of them worked earlier on orders by KB-11.

At the moment all principal persons have been re-vetted except for Prof. Meiman N S — head of the computation bureau.

I was informed by Cde. Pavlov N I that doubt exists on whether N S Meiman will be given access to this work with L D Landau, and I was told to discuss possible candidates for replacing him.

We sent the materials needed for re-vetting Cde. Meiman on 8 March 1952 but are still waiting for a reply.

Consequently, it is not possible to allow the computation bureau to start this work, while the Institute has no other mathematicians capable of heading the bureau.

As a result, L D Landau's work on the 'sloika' has stood practically still for nearly a month now.

As shown by the attached information sheet, Meiman has worked on the KB-11 objects, RDS-6, and the 'tube' ever since 1948 and his successful work had been specially noted.

I request here that You give an instruction to speed up the solution of the issue with the possibility of involving Cde. Meiman in the work on the 'sloika'.

What needs to be taken into account is a delay of 5 months that would be inevitable if Meiman were to be replaced by somebody else of suitable skills, because even a fully qualified mathematician would have to spend that amount of time to master the complicated methods of computing.

A Aleksandrov''

This letter bears the following resolution by L P Beria:

''1. To Cde. Zavenyagin A P

Consider together with Cdes. Kurchatov and Pavlov the application from Cdes. Aleksandrov, Tamm, and Landau.

Please contact Cde. Ignatiev S D.

Inform me of Your suggestions.

2. To Cde. Ignatiev S D

Please consider and let me know what you think. L Beria 5 May 1952.''

Author's note: *Ignatiev S D — Minister of State Security*.

In accordance with this assignment, A P Zavenyagin and N I Pavlov sent L P Beria a letter with the following [88]:

''In compliance with Your instructions, we considered the application of Aleksandrov, Tamm, and Landau concerning the permission for Cde. Meiman N S to join in the work on RDS-6s in his capacity as head of the Computation Bureau of the Institute for Physical Problems of the USSR Academy of Sciences.

In view of the fact that Cde. Meiman has worked at the Institute for Physical Problems since 1948 and took part in a number of assignments for KB-11 (calculations of efficiency of products, study of the process of deuterium detonation, etc.), we believe that in order to ensure meeting the deadlines on computational projects for the RDS-6s product, Cde.

Meiman must be given access to this work for a duration of up to six months.

To prepare a replacement for Cde. Meiman, we consider it expedient to immediately find a deputy for him. As such, we suggest the candidature of Cde. Molchanov A M.

Cde. Molchanov, Candidate of Physicomathematical Sciences (CdSc), currently heads the computational group at the Mathematical Institute of the USSR Academy of Sciences, which has been conducting mathematical studies for the RDS-6t product during the last six months.

Academicians Keldysh and Petrovskii characterize Cde. Molchanov as a talented young mathematician.

Cde. Aleksandrov A P requests permission to hire Cde. Molchanov as deputy head of the Computation Bureau of the Institute for Physical Problems.

These proposals were agreed on with Cde. Ignatiev.''

As a result of this intervention by top brass, N S Meiman was given access to RDS-6s work. As we see from A P Aleksandrov's letter, this led, in addition to the fraying of nerves of the two academicians, to a delay in RDS-6s computations.

On 7 May 1952, the highest management of the Soviet Atomic Project, B L Vannikov, A P Zavenyagin, I V Kurchatov, Yu B Khariton, E P Slavsky, N I Pavlov, and P M Zernov sent L P Beria a revised draft of a resolution of the USSR Council of Ministers on creating RDS-6s [89]. Item 1 of the project read:

``As extending the Resolution No. 5373-2333, charge:

a) The Institute for Physical Problems of the USSR Academy of Sciences (Cdes. Aleksandrov and Landau) with executing the calculations for the explosion of the model RDS-6s. Deadline: December 1952.''

Items 12 and 19 read:

``12. Oblige the PGU and the USSR Academy of Sciences to direct graduates of the training courses of computational mathematicians to work in Landau's department (Institute for Physical Problems of the USSR Academy of Sciences) — 6 people. [...]

19. Increase the staff of the Institute for Physical Problems of the USSR Academy of Sciences (Cde. Landau's department) by 4 engineers and 4 computational mathematicians.''

The head of this group, L D Landau, systematically sent reports on the accomplished work for RDS-6s to the top management of the PGU. In his handwritten report of 26 July 1952 to A P Zavenyagin he wrote [90]:

``Reporting on the progress of work on the MC in July 1952. During this period the group:

1. Developed a method of calculations for the passage of a heat wave through the first heavy shell.

2. Developed a method of calculations for the process of 'collapse' of light layers — their heating, compression and progress of reaction in them.

3. Tested the efficiency of the developed method of integration of the heat transfer equation. Introduced an improvement for conducting computations near the center. Started systematic computational runs for the object.''

The reverse side of the report (signed by Landau) is marked with this: ``Prepared in a single copy without drafts, executed by Lifshitz E M, 26.07.1952.''

At the beginning of July 1952, the IPP sent the FMD the ``Plan of works on the MC for the 2nd half of 1952'' in which it was indicated [91]:

``Plan of the works on the MC for the 2nd half of 1952. For execution by: theoretical department and mathematical bureau in compliance with the approved list. Head of the project: Acad. L D Landau

Stage-by-stage work content	Execution deadline	Comment
1. Development of the method of calculating the process of 'collapse' of light layers. Study of propagation of shock waves in these layers.	25.07.	
2. Testing the efficiency of the developed methods of numerical integration of the differential equation of heat transfer.	25.07.	
3. Progress of the process in the object until the first light layer is heated. Burning of the central core and propagation of the thermal wave in the first light shell.	1.09.	Between 25.07 and 1.09 work will mostly proceed in the mathematical bureau. This is the time of planned vacations for L D Landau (from 28.07 to 30.08). Responsibility for and monitoring the progress of the bureau on the side of physicists during this time is entrusted to I M Khalatnikov.
4. Process of 'collapse' of the first light shell and progress of reaction.	15.10.	
5. Evolution of the process after the 1st light shell 'collapses'. Shock wave enters heavy material. Turbulent mixing in the object. Process propagates through the second heavy shell. Process of 'collapse' in the 1st light shell.*	25.11.	
6. Heat reaches the outer shell of the object. Origin and development of the process of spreading out of material. Concluding stage of the process in the object.	20.12.	
7. Preparation of graphic report that records the evolution of the process in the object.	31.12.	

Signed Landau (Acad. L D Landau).''

In a similar report for September 1952 sent to A P Zavenyagin on 1 October 1952, Landau wrote [92]:

``Reporting on the progress of work on the MC in September.

It was found in the course of systematic computations that the method developed for modeling the process of multiplication of particles becomes practically unusable after the narrow layer begins to 'collapse'. This factor made it necessary to develop a new method, which delayed the stage of systematic computations of the object. By now we have developed a new technique and computations have resumed.

During this month we also continued theoretical work on calculations of shock waves entering wide layers from narrow ones right after their 'collapse'.

L Landau. 1. X.52.''

* 1st light shell — as in the document. V I Ritus gives evidence that 2nd light shell should be read here. (*Author's note to English proof.*)

Landau's report bears the following remark made by FMD staffer V S Komel'kov on 13 October 1952: "Cdes. Tamm I E and Sakharov A D were familiarizing themselves with the status of work at the IPP."

It must be stressed that Landau was in the know on the RDS research conducted at other organizations — the management of the Atomic Project promoted it. For instance, on 17 January 1952 Yu B Khariton made a request that P M Zernov instruct M G Meshcheryakov to send the report by V A Davidenko et al. on measuring cross sections of the reactions $D(d,n)He^3$ and $T(d,n)He^4$ to the IPP for L D Landau to read. On 27 March 1952, he requested that P M Zernov send the IPP the report "Preliminary deliberations on the methods for solving problems like those of the main task and an Appendix to the report "List of notations" for Landau's information. On 5 April 1952, a report by A D Sakharov and V I Ritus, "Formulation of the problem on the action of the MC", was forwarded to Landau.[2] Reports by researchers at ICP, PIAS, and A N Tikhonov's bureau were also sent, and we know of a considerable number of such cases.

9. Evaluation of L D Landau's contribution

The archival documents quoted or reproduced in this paper show that L D Landau and his small group made a substantial contribution to the exceptionally complicated computational justification of both the atomic and hydrogen bombs. In fact, in addition to the documents presented above, there are some documentary evidences from his contemporaries that we demonstrate below. One of the telltale witness accounts is an unbiased and competent opinion about the relevant activities of L D Landau left by K I Shchelkin who played a direct role in the events described in this article and sent his opinion to the FMD on 18 May 1952 [93]:

"L D Landau's work contributed to all the most important fields of work at KB-11. These can be subsumed under the following principal types:

1. Detonation of conventional explosives.

2. Quantitative theory of the nuclear chain explosion and the calculation of efficiency of KB-11 designs, both finalized and those under development.

3. Work on the theory of the RDS-6t product (interrupted at the moment in view of the new assignment on RDS-6s).

4. Development of the methods of calculating the nuclear chain explosion and thermonuclear explosion, and calculations of the efficiency of RDS-6s (work started in January 1952).

L D Landau supervised the work of a small group of physicists (Doctor of Sciences Lifshitz, Candidates of Sciences Khalatnikov, D'yakov, Sivukhin) and a mathematical group of about 15 people.

Presented below are the results obtained by Landau and his group in the fields enumerated above:

1. Detonation of conventional explosives

Work in this field was carried out in collaboration with K I Stanyukovich in 1944 – 1945, not on special assignments but in connection with the general aspects of the theory of explosives. Landau and Stanyukovich pointed out that the explosion products — matter at a temperature of several thousand degrees and at pressures of hundreds of thousands of atmospheres — cannot be treated as gas consisting of rigid incompressible molecules, as is customary in the literature. Landau and Stanyukovich advanced and substantiated the notion of explosion products as elastic liquid in which the elasticity of molecules, not their thermal motion, is responsible for high pressure. From the data on the rate of detonation of explosives with different densities they deduced the law describing pressure as a function of density. The work was published in *Doklady Akad. Nauk SSSR*. When in 1946 KB-11 began work on the products with compressed charge, the equation proposed by Landau and Stanyukovich was used. These equations and theoretical calculations at KB-11 and the Mathematical Institute of the USSR Academy of Sciences based on them were widely tested and confirmed in direct experiments.

2. Quantitative theory of the nuclear chain explosion

Landau and his group were involved in the development of the theory of the nuclear chain explosion at the end of 1947. By that time a number of calculations of the critical masses and neutron multiplication rates in an above-critical mass of active material were already carried out by KB-11 and by a group of researchers at the Institute of Chemical Physics working on task orders by KB-11.

Neutron multiplication gives rise to energy release and very high pressure increase; an explosion results — the main charge expands and the process is terminated, even though only a fraction of the active material is consumed. Before Landau's work, only an approximate semiquantitative theory of the explosion process was available, which correctly identified the role of such factors as supercriticality and multiplication rate, although it could not provide the required accuracy in efficiency calculations.

Landau and his group developed for two years the quantitative theory that made it possible to calculate the explosion power with sufficient accuracy, and the main

[2] A very interesting communication was received by the editors in the course of preparation of this article from Vladimir Ivanovich Ritus, contemporary and participant of the events at that time. An oversight made it impossible to take it into account when preparing the Russian version of the text for publication. This unfortunate mishap is corrected here. V I Ritus pointed out that printed on page 978 of G V Kiselev's article, right-hand column, line 15 f.a. was: "On 5 April 1952 a *report* by A D Sakharov and Ritus "Formulation of the problem on the action of the MC" was forwarded to Landau". V I Ritus maintains, however, that this was not a **report** but the **main task** formulated and signed by A D Sakharov and V I Ritus and that this even follows from the title of the document "**Formulation of the problem** on the action of the MC". After this V I Ritus remarks: "It is highly probable that it was precisely concerning this job assignment signed by Sakharov and myself and forwarded on 5 April 1952 that Landau sent to I E Tamm the following top secret letter of 11 April 1952:

"Dear Igor Evgenievich,

Unfortunately, the very instructive note that arrived from you does not give figures to the values of the velocities of particles of each group. Please send them along as soon as possible.

Yours L Landau 11/IV- 52."

A facsimile of this letter was published in the article by Yu A Romanov "Remembering the Teacher" [*Usp. Fiz. Nauk* **166** 195 (1996), p. 197; *Phys. Usp.* **39** 179 (1996), p. 181]. Landau refers to this assignment as 'note' because it was written on one large "checked sheet with text in greenish-blue ink on both sides". Moreover, top secrecy required a very specific code of communication. However, what a high mark given to this "note"! The reader can learn more about this 'note' in my article "The history of one task" published in the journal *Priroda* No. 12 (2004) on pp. 57 – 61".

Another active participant of these events Isaak Markovich Khalatnikov recalls in his remarkable new book of memoirs "Dau, Centaur and others (Top nonsecret)" (Moscow: Fizmatlit, 2008) on pp. 45 – 47 a dramatic story connected with this "checked sheet with text in greenish-blue ink on both sides" also mentioned in A D Sakharov's *Memoirs* (New York: Knopf, 1990) Ch. 6, p. 103. [In Russian (Moscow: "Prava cheloveka", 1996) Vol. 1, p. 151]. (*Author's addendments to English proof.*)

mathematical computations were carried out by the Institute for Physical Problems Mathematical Bureau led by Meiman, and a number of assignments were done in Tikhonov's bureau on Landau's task orders.

The work is presented in 22 reports.

To develop the theory of the process, Landau studied the properties of active substances (pressure, heat capacity, thermal conduction) under the conditions reached in real explosions. Then he developed a method for describing the process with a set of differential equations in total derivatives. Integration of these equations yielded the law of expansion of the active sphere, the law of motion of the shell surrounding the sphere, the temperature curves in the active sphere and the shell, the shell of neutron multiplication, and the progress of the nuclear process. These calculations yielded the total amount of burnt material and the total amount of energy released.

Calculations for a large number of specific cases were carried out, making it possible to construct a convenient generalizing formula for the explosion power as a function of a design parameter.

Calculations were done for systems undergoing test explosions and for systems prepared for explosion.

3. Work on the detonation of deuterium (D, D)

Landau and his group joined the work on the initiation of the deuterium detonation in accordance with a governmental resolution of 26 February 1950. Prior to this, work at KB-11 and commissioned organizations clarified the main qualitative features of the problem. At this stage, Landau played a consultative role and made valuable suggestions on, among other points, the theory of Comptonization (one of the more difficult and important aspects of the problem).

To solve the main problem of unrestricted propagation of deuterium detonation in a cylindrical charge, one needs an exact quantitative theory of processes that occur in a thermonuclear reaction. Developing this theory was assigned to Landau's group, which carried out the following work.

The rates of thermonuclear reactions at high temperatures were recalculated using experimental data. The free paths and slowing-down times of particles produced in nuclear reactions, and energy transfer from these particles to nuclei and electrons were calculated. The accuracy of the calculations of the primary emission of quanta was improved. The laws of single scattering of quanta in hot matter were deduced.

When the work began, the possibility of propagation of a process of energy transfer by fast particles without a shock wave could not be excluded. This possibility was checked and rejected by Landau's group as a result of compiling and integrating one-dimensional equations of the deuterium detonation.

The analysis of the solution for propagation in the presence of a shock wave required developing new methodology for a complex gas dynamics problem. Landau began working on a direct, conceptually reliable but very labor-consuming method of analyzing nonstationary processes. He developed effective methods of speeding up such computations. The methods he developed can also be utilized in the problem of initiation of RDS-6t and in other problems involving calculations for hydrogen products.

The work of Landau's group on the detonation of deuterium was presented in 9 reports.

4. Work on the theory of the multilayer charge

In 1949, when Landau's opinion was sought concerning approaches to the theoretical treatment of the mixing of the layers in a multilayer charge during explosion, which substantially affects the efficiency of this product, Landau pointed to a method of calculating turbulence in the mixing of layers which was subsequently — and with Landau's continual consulting — used in this instance and became the basis for all estimates of mixing phenomena in multilayer charges.

In 1951, when working on the D–D issue, Landau subjected to systematic analysis the aspect of possible methods of numerical integration of differential equations from the standpoint of efficiency, reliability, and accuracy of the methods. He is employing the results of this study now to construct a method of calculations for the effects of a multilayer charge, such that it would be possible to take account of certain peculiarities of the hydrodynamical behavior of a layered shell in the course of an explosion. The unusual behavior (the so-called 'bumpiness'), which harmfully affects the efficiency of the product, has not been taken into account so far with the required accuracy because of the complexity of the issue and the absence of efficient methods for solving it.

In compliance with the decision of the Government of 29 December 1951, at the beginning of 1952 Landau started calculations with the acting model of a multilayer charge intended for pilot testing. This is precisely the case in which comparing theory and experiment and extraction of reliable data for designing the final version makes an actual exact calculation a must, and Landau's method provides that.

At the moment, Landau's group, having analyzed the physical side of the phenomena that take place in a multilayer charge, is preparing joint task orders for the Mathematical Bureau.

A very substantial contribution made by Landau to the development of the theoretical foundation for our technical capabilities is closely connected with Landau's talent for combining the art of profound theoretical analysis of physical phenomena with his ability to find efficient methods of quantitative calculations for extremely complicated problems, which led him to draw out relatively simple functional relations that can be directly applied to solving practical problems.''

The original of this document, stored in the Rosatom Archive (Fond 24, Delo 61464, Listy 20–24), is signed by K I Shchelkin, and is marked on the reverse side with: ''typed by Khariton.''

IPP Director A P Aleksandrov gave another important evaluation of Landau's work in his letter to A P Zavenyagin, in which he wrote [94]:

''1. At the beginning of 1947, Academician L D Landau received assignments from KB-11. The first assignment was carried out by Academician Landau, Professor, DSc Lifshitz and CdSc Khalatnikov, and the computation bureau specially organized for this work and headed by Prof. N S Meiman. In 1947–1949, Landau conducted theoretical investigations of the explosion process and calculated the efficiency of an explosion of an active sphere. He considered general methods of neutron multiplication in these systems and methods for following the hydrodynamic picture of the explosion. He ran computations for about 100 various versions of product design (bare sphere, sphere in a shell, sphere composed of different active materials of different degrees of supercriticality).

As a result of generalization of the data obtained, simple interpolation formulas were constructed, which make it possible to evaluate quite simply the role of all these factors and their effect on the efficiency of the product.

Consequently, the results obtained by L D Landau permitted the selection of the optimal design of the products.

The results of this program can be found in IPP reports kept in cipher 'OTF' from No. 1 to No. 24 and in a number of letters to Yu B Khariton.

2. In 1950 – 1951, work was conducted on clarifying the possibility of detonation in the 'Tube' suggested by Ya B Zel'dovich. Calculations were carried out on establishing the physical characteristics of matter at very high temperatures (hundreds of millions of degrees), which was necessary for understanding the explosion process. This brought out a new and important factor — long mean free paths of fast particles released in the reaction; their role in the process thus becomes especially important. A question that arose in this connection was whether this role was so important that it would dominate the entire process. Methods were worked out to compute the course of the process with this mechanism of detonation propagation, but once the computations were carried out they showed that this process is insufficient to sustain steady-state detonation and that detonation due to the shock wave unfolds in parallel with this process.

At the same time, other approaches were analyzed, aimed at constructing approximate methods of calculations for the hydrodynamic regime containing a shock wave.

By the spring of 1951, the work revealed a pattern of extremely complex phenomena, greatly exceeding the expected difficulties, and a new plan was composed in which Landau's group was made responsible for two lines of investigation:

1. Work on the Compton effect, which has been completed and at the moment is becoming the basic starting point for Pomeranchuk's group.

2. Work on solving idealized gas dynamics problems by integrating exact equations of nonstationary motion. No one has ever attempted to solve problems of this sort, so that absolutely new mathematical methods had to be constructed, and Landau's group accomplished that. The significance of the methods developed goes far beyond the limits of this problem (the tube) and they can be successfully applied to resolving other similar issues, including problems with the efficiency of a conventional product and a 'sloika' gadget. Taking part in this work, in addition to L D Landau's colleagues listed earlier, was S P D'yakov, Candidate of Physicomathematical Sciences.

The results of the work were presented in OTF reports Nos 25 – 38.

3. At the beginning of March 1952, the group headed by Landau was transferred to working on the sloika.

Earlier, L D Landau personally took part in this program as a consultant; in particular, he proposed the main conceptual methods for calculating the very important mixing of 'light' and 'heavy' layers.

All the reports by Landau's group demonstrate, as we see from the above, that the issues they considered were hugely important; we do not have direct references from KB-11 and the representative conclusions presented here are based on our own opinions.''

Appended to this letter from A P Aleksandrov was a list of research reports from Landau's group over the period from 1947 to 1952, which is a documentary evidence of the intense work of Landau and his group; the list is reproduced below:

''1947 – 1948

1. Report OTF/1. Landau L D, Khalatnikov I M. Efficiency of an uninsulated active sphere (sent to PGU — Pervukhin, LIP — Sobolev, ICP — Semenov, Zel'dovich on 16.03.48).

2. Report OTF/2. Landau L D, Lifshitz E M, Khalatnikov I M. On multiplication of *zero points* under critical conditions (sent to PGU — Pervukhin, LIP — Sobolev, ICP — Semenov, Zel'dovich on 16.03.48).

3. Report OTF/3. Landau L D, Lifshitz E M, Khalatnikov I M. Hydrodynamic study of the process of expansion of a sphere. I (sent to PGU — Pervukhin, LIP — Sobolev, ICP — Semenov, Zel'dovich on 16.03.48).

4. Report OTF/4. Landau L D, Pomeranchuk I Ya, Akhiezer A I, Khalatnikov I M. Heat conduction of *tin* (sent to PGU — Pervukhin, LIP — Sobolev, ICP — Semenov, Zel'dovich on 16.03.48).

5. Report OTF/5. Landau L D, Khalatnikov I M. Efficiency of an infinitely insulated active sphere that does not interact with zero points and radiation. I (sent to PGU — Pervukhin, ICP — Semenov on 27.03.1948, LIP — Sobolev on 15.07.48).

6. Report OTF/6. Landau L D, Khalatnikov I M. Efficiency of an infinitely insulated active sphere that does not interact with zero points and radiation. II (sent to LIP — Sobolev on 17.05.48, PGU — Khariton on 17.05.48, ICP — Semenov, Zel'dovich on 17.05.48).

7. Report OTF/7. Landau L D, Khalatnikov I M. On the effect of infinite insulation interacting with radiation on the efficiency of active spheres (sent to LIP — Sobolev, PGU — Khariton, ICP — Semenov, Zel'dovich on 17.05.48).

8. Report OTF/8. Landau L D, Khalatnikov I M. Adiabatic expansion of an infinitely insulated active sphere that does not interact with *zero points* (sent to LIP — Sobolev, PGU — Khariton, ICP — Semenov, Zel'dovich on 17.05.48).

9. Report OTF/9. Landau L D, Khalatnikov I M. Critical dimensions of insulated active spheres (sent to PGU — Khariton, LIP — Sobolev on 7.06.1948, PGU — Pavlov on 31.03.52).

10. Report OTF/10. Landau L D, Khalatnikov I M. Time dependence of multiplication of *zero points* in insulated active spheres (sent to PGU — Khariton, LIP — Sobolev on 7.06.1948, PGU — Pavlov on 31.03.52).

11. Report OTF/11. Landau L D, Khalatnikov I M. Efficiency of an uninsulated active sphere (sent to Tikhonov on 5.07.48).

12. Report OTF/12. Landau L D, Lifshitz E M, Khalatnikov I M. Hydrodynamic study of the sphere process (sent to Tikhonov on 5.07.48).

13. Report OTF/13. Landau L D, Lifshitz E M, Khalatnikov I M, Meiman N S. Hydrodynamic investigation of the process of expansion of a sphere (sent to PGU — Khariton on 28.10.48, PGU — Pavlov on 21.03.52).

14. Report OTF/14. Landau L D, Lifshitz E M, Khalatnikov I M. Complete set of integro-differential equations describing the burning process (sent to PGU — Khariton on 28.10.48, PGU — Pavlov on 21.03.52).

15. Report OTF/15. Khalatnikov I M. Critical sizes of spheres with arbitrary distribution of active matter (sent to PGU — Khariton on 28.10.48, PGU — Pavlov on 21.03.52).

16. Report OTF/16. Khalatnikov I M. Critical sizes of spheres (sent to PGU — Khariton on 28.10.48).

17. Report OTF/17. Landau L D, Khalatnikov I M. Distribution function for *zero points* in active spheres (sent

to PGU — Khariton on 28.10.48).

18. Report OTF/18. Khalatnikov I M. Time dependence of multiplication of *zero points* in nonuniform spheres (sent to PGU — Khariton, PGU — Zel'dovich on 28.12.48, PGU — Pavlov on 21.03.52).

19. Report OTF/19. Khalatnikov I M. Some remarks on economically expedient mass distribution in active spheres (sent to PGU — Khariton on 31.10.48).

20. Report OTF/20. Landau L D, Lifshitz E M, Khalatnikov I M. Hydrodynamic study of the process of expansion of a sphere. III (sent to PGU — Khariton, PGU — Zel'dovich on 28.12.48).

1949

21. Report OTF/22x). Landau L D, Lifshitz E M, Khalatnikov I M. Hydrodynamic study of the process of expansion of spheres. IV (sent to PGU — Khariton on 22.04.49).

22. Report OTF/23. Landau L D, Lifshitz E M, Khalatnikov I M. Hydrodynamic study of the process of expansion of spheres. IV (sent to PGU — Khariton on 6.05.49).

23. Report OTF/24. Landau L D, Lifshitz E M, Khalatnikov I M. Interpolation formulas for the efficiency of active spheres (sent to PGU — Khariton on 6.07.49).

24. Report OTF/25. Landau L D, Lifshitz E M, Khalatnikov I M. On the theory o *deuterium* detonation. I (sent to PGU — Khariton on 10.07.49).

25. Report OTF/26. Landau L D, Lifshitz E M, Khalatnikov I M, D'yakov S P. On the theory of *deuterium* detonation. II (sent to PGU — Khariton on 10.07.49).

26. Report OTF/27. Landau L D, Lifshitz E M, Khalatnikov I M, D'yakov S P. On the theory of *deuterium* detonation. III (sent to PGU — Khariton on 10.07.49).

1951

27. Report OTF/28. Landau L D, Lifshitz E M, Khalatnikov I M. On the possibility of detonating *deuterium* in a tube (sent to PGU — Pavlov on 3.02.51).

28. Report OTF/29. Landau L D, Lifshitz E M, Khalatnikov I M. Report No. 4. Effect of the finite radius of a cylinder on the processes of energy transfer by fast particles (sent to PGU — Pavlov on 3.02.51, PGU — Khariton on 18.04.51, Keldysh on 14.07.51).

29. Report OTF/30. Landau L D, Lifshitz E M, Khalatnikov I M. Report No. 1 (sent to Laboratory 'V' — Blokhintsev, Keldysh on 14.05.51).

30. Report OTF/31. Landau L D, Lifshitz E M, Khalatnikov I M, D'yakov S P. Report No. 2 (sent to Laboratory 'V' — Blokhintsev, Keldysh on 14.05.51).

31. Report OTF/32. Landau L D, Lifshitz E M, Khalatnikov I M, D'yakov S P. Report No. 3 (sent to Laboratory 'V' — Blokhintsev, Keldysh on 14.05.51).

32. Report OTF/33. Landau L D, Lifshitz E M, Khalatnikov I M, D'yakov S P. Report No. 4. Effect of the finite radius of a cylinder on the processes of energy transfer by fast particles (sent to Laboratory 'V' — Blokhintsev on 14.05.51).

33. Report OTF/34. Landau L D, Lifshitz E M, Khalatnikov I M, D'yakov S P. Report No. 5 (sent to PGU — Khariton on 25.07.51, PGU — Pavlov on 10.03.52).

34. Report OTF/35. Landau L D, Lifshitz E M. On the reflection of weak discontinuity from a sonic line (sent to PGU — Khariton, Keldysh on 7.01.51).

1952

35. Report OTF/36. Landau L D, Lifshitz E M. A method for solving equations of the idealized hydrodynamic problem. Report No. 7 (sent to PGU — Khariton, Keldysh on 3.03.52).

36. Report OTF/37. Landau L D, Lifshitz E M, Khalatnikov I M, Meiman N S. Integration of the sets of partial differential equations of the hyperbolic type by the grid method. Report No. 8 (sent to PGU — Khariton, Keldysh on 3.03.52).

37. Report OTF/38. Landau L D, Lifshitz E M, Khalatnikov I M, D'yakov S P. One-dimensional equations of detonation in system 'T' (sent to PGU — Khariton, Pavlov for Blokhintsev on 10.03.51)."

On 20 May 1952, the Directors of the PGU A P Zavenyagin and N I Pavlov sent L P Beria, in compliance with his order, "an information sheet on the works carried out by Academician L D Landau on task orders by PGU" in which they partly used the information provided by K I Shchelkin [95]:

"Academician Landau L D is charged with performing the research work on physical phenomena occuring in the process of an explosion of plutonium, uranium-235, and deuterium and the mechanism of development of the explosion and its efficiency.

1. Detonation of conventional explosives. [...]

2. In 1947–1949, Landau was charged by PGU with developing the theory of finding the efficiency of various design versions of the RDS product. We did consider the data on the possible values of efficiency but had no information on, or methods for, determining efficiency and were faced with lacking specific calculations of efficiency.

The work that he presented in 22 reports was original and innovative and gave important help to KB-11 towards understanding the processes occurring during an explosion of the bomb.

It should be noted that the accuracy in finding efficiency by the technique developed by Landau proved insufficient, so that in the case of RDS-1 and RDS-2 products the actual efficiency was found to be higher by 30%, and in the case of RDS-3 by 10%.

3. In 1950, Academician Landau was entrusted with the work on deuterium detonation and clarifying the feasibility of creating the RDS-6t product.

In 1950–1951, Landau carried out much work establishing the nature and courses of various nuclear processes involved in deuterium detonation (mean free paths of fast particles, energy transfer by fast particles to nuclei and electrons, energy loss caused by gamma radiation, etc.).

When studying the conditions for deuterium detonation, Landau assumed that detonation caused by fast particles played a decisive role and underestimated the effect on detonation of the shock wave originating as a result of the explosion of the initiating bomb.

This need to take into account the effect of the shock wave on deuterium detonation made the problem of elaborating the theory of deuterium detonation more complicated and demanded that a new mathematical method be devised; it also meant a great deal of additional calculations. By now, Landau has completed these additional studies entailed by the role played by the shock wave.

Has Landau answered the question of whether the RDS-6t product is possible or not? Perhaps not. This work will require more effort and considerable time.

As the problem is so complex and the volume of work is so large, a decision by the Government involved additional groups of Academician Keldysh at the Mathematical Institute and Corresponding Member of the USSR Academy of Sciences Blokhintsev at Laboratory 'V' of the PGU in order to speed up reaching a decision on whether the RDS-6t product is a possibility.

Landau's work on the theory of deuterium detonation was described in 9 reports.

4. In view of the need for the speediest completion of the work on the RDS-6s product at the beginning of 1952 Academician Landau's group was transferred by a decision of the Government to calculations for the model of the RDS-6s product (mechanism of explosion, explosive power, the phenomenon of mixing of the heavy and light layers).

During the past months of 1952, Landau's group has been analyzing the physical side of the phenomena taking place in the multilayer charge, and is preparing task orders for the Mathematical Institute.

The physicists taking part in the work by the orders of PGU regard Academician Landau as undoubtedly the number 1 physics theorist in the USSR. His work for the KB-11 was carried out at a high scientific level and was used at the KB-11 as a basis of calculations of compression, efficiency of products, and processes taking place in deuterium detonation."

An assessment of the importance of the work by Landau's group and Landau personally is found in the document "A model of the RDS-6S product" drafted by A D Sakharov, I E Tamm, and Ya B Zel'dovich on 17 July 1953 before the test explosion of RDS-6s version of an H-bomb on 12 August 1953 [96]. It consists of the following sections:

1. Basic principle and main characteristics of the RDS-6s product.

2. Investigation of processes taking place after triggering RDS-6s:

A. Nuclear research

B. Analysis of compression

C. Mixing of layers in the process of explosion

D. Calculation of processes in a nuclear explosion and explosive power of the product.

3. Analysis of reliability of the RDS-6s product.

4. Targets for and methods of testing the RDS-6s product.

According to an established procedure, certain terms such as neutrons, KB-11, RDS-6s, nuclear explosion, and some others were written in by A D Sakharov's hand (italicized).

In this description, the authors of the document wrote [96]:

"Tikhonov's and L D Landau's groups developed, on task orders by KB-11, methods of 'detailed' calculations of the process of an *explosion*.

The idea of 'detailed' calculation boils down to the following. The total time interval in which the process of *explosion* plays out is split into a series of short intervals, i.e., time steps (whose total number is about 100). The process of an *explosion* is calculated step by step beginning with the destruction of the *neutron detonator* until the last stages when the density of the product drops so low as a result of expansion that all the *nuclear* (*neutron and thermonuclear*) reactions are practically terminated. To take into account the interaction between various parts of the system, it is subdivided into a sequence of segments along the radius (their number in the calculation amounts to about 30) and in each of them the values of all functions of temperature, density of matter, and number densities of *neutrons* of three different 'energy' groups are found for each time step.

The development of mathematical methods for the detailed calculation carried out by the groups of Landau L D and Tikhonov A N on orders by *KB-11* called for a serious research effort and large amounts of computations. Twelve detailed computation runs of *hydrogen* products[x)] were conducted in search of an optimum version of *RDS-6S* and for methodical studies. The number of arithmetic operations executed for this runs into many tens of millions.

Certain points of principle need emphasizing. The method of computations developed for this work was such that errors inevitable in such cumbersome computations did not accumulate and did not cause a serious error in the final result. The solution to this problem opens a way, in particular, of employing electronic computers replacing slow time- and labor-consuming manual calculations.

Special difficulties in the problem of calculations for RDS-6S (ultimately overcome only in 1952 by Landau L D) stemmed from shock waves originating in the product and generated by the compression of light layers at the stage of the *nuclear explosion* and caused by the layered structure of the products.

A number of values of heat conductivity and the equation of state of *uranium* at a temperature of *100 million* degrees, and the characteristics of mixing, viscosity, and diffusion required for computations of the *process of an explosion* were calculated at the Physics Institute of the USSR Academy of Sciences. An essential part of preliminary work at *KB-11* consisted of working out the methodology of calculations in the process of the *explosion*."

Footnote to the document: x) "7 calculations at Tikhonov's bureau, and 3 calculations at Landau's bureau."

The archival documents presented in the this article are evidence of Academician L D Landau's momentous contribution to the calculational justification of atomic and hydrogen weapons at the early stage of the Soviet Atomic Project.

10. Conclusion

The creation of nuclear and hydrogen weapons in the former USSR constitutes an extremely important stage in the history of atomic science and industry in the USSR, which made it possible to provide a necessary and sufficient level of security and defense of the country. Participating in developing the first versions of the atomic and hydrogen bombs were a large number of well-known Soviet scientists and engineers.

Many outstanding scientists contributed to the success of the Atomic Project. Their role has been written up in sufficient detail in various publications, including the pages of *Physics – Uspekhi* (see Refs [97 – 106]). However, the names of many participants and their contributions to the common cause remain insufficiently known, owing to well-known circumstances. Among others, the role of the brilliant Soviet scientist Academician L D Landau and his small circle of colleagues — small in number but not in brilliance — has not been adequately described.

Fortunately, in the year of the 100th anniversary of the birth of Academician Lev Davidovich Landau, it has become possible to present to the reader a review of the enormous contribution to the Atomic Project made by Lev Davidovich himself and by his disciples and colleagues. The article you read now makes it possible to learn of these previously unknown scientific achievements of L D Landau and his colleagues in the Soviet Atomic Project. This review of previously classified documents shows the enormous role that L D Landau played in the shared success; we believe that this publication throws light on another (poorly known) facet of his extraordinary personality.

Appendix 1. Abstracts of reports presented at the meeting on RDS-6t of 8–9 January 1952 [75]:

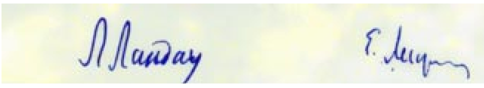
On the reflection of weak discontinuity from the sonic line

L D Landau, E M Lifshitz

1. To clarify the qualitative nature of motion in idealized gas dynamics problems, peculiarities of flow were investigated near the intersection point of a weak discontinuity starting at the edge of the 'lentil' and the transition line separating the subsonic from the supersonic region. The study was conducted using the Chaplygin gas dynamics equation in the form of the Tricomi equation simplified for transonic flow.

2. It is shown that a weak discontinuity must 'bounce' backward from the intersection point and that the incoming and reflected discontinuities at the intersection point are tangent to the transition line, and this line has an inflection point. The distribution of velocities at the reflected discontinuity has an unusual logarithmic singularity. In the first approximation, nonadiabaticity of motion and the presence of vortices do not affect this pattern.

A detailed presentation of the work is given in the report OTF-35.



L Landau, E Lifshitz Mb. 33sd to ref. number 026sd of 17.01.52, Mb. 44 iz pp. 34, 24-18-11

On the solution to the two-dimensional nonstationary gas dynamics problem

L D Landau, E M Lifshitz, N S Meiman, I M Khalatnikov, S P D'yakov

1. Toroidal coordinates turn to be the most convenient coordinates for this problem. The origin of the toroidal reference frame is chosen in the corner of the 'lentil' (the point of intersection of the shock wave and the wall).

2. The method of numerical solution of partial differential equations with large time steps for the one-dimensional case (a single coordinate) developed by us cannot be completely transferred to the case of a two-dimensional problem. In the latter case no characteristic combinations of variables are available with which gas dynamics equations allow unidirectional computation away from the shock wave or sonic line.

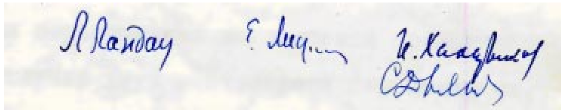
3. However, gas dynamics equations in the two-dimensional case can be rewritten in such a way that they contain characteristic combinations which permit finding their values by unidirectional computing along one of the coordinates, using large time steps.

4. The numerical procedure that we developed for solving the two-dimensional problem includes unidirectional computation along one of the coordinates and conventional grid computations along the second coordinate.

In this case, naturally, there emerges the condition restricting the time steps. In fact, we need to take into account here that the flow pattern varies much less along one coordinate than along the other.

Using unidirectional computation in the coordinate along which velocity varies more rapidly, we achieve a situation in which the condition restricting computation in time is only related to the size of the step in the coordinate along which the variables change slowly.

In this manner, computations can be speeded up by a factor of about five to six in comparison with the conventional computation methods.



24-18-11 pp. 35-36 mb. 045iz

Integration of hydrodynamical equations by the grid method

L D Landau, N S Meiman, I M Khalatnikov

1. Sets of hyperbolic-type partial differential equations with two independent variables are typically integrated by the method of characteristics. Computations by characteristics have their advantages, but those types of computations in the case of two variables are very cumbersome. It becomes absolutely unwieldy when one attempts to transfer it to the case of three independent variables.

In contrast to the characteristics method, the case of three independent variables for the grid method is no more complicated in principle than the case of two independent variables. Finally, even in the case of two independent variables the grid method is considerably simpler and less labor intensive than the method of characteristics. The difference operator, which in the grid method replaces the differential operator, is a perturbed operator in relation to the differential operator and therefore we inevitably have some sort of perturbation at each step of the computations even if these were ideally accurate and we neglected inevitable rounding-off errors. It follows then that only with grid and difference schemes that satisfy certain stability criteria do grid computations approximate the solution of a set of differential equations. Otherwise, the computations become completely meaningless. We have clarified the criteria that must be met by the grids and by difference schemes, transforming them to a complete algebraic form and therefore developing a computational method on grids. We need to especially emphasize that we first detected and explained the fact that under certain conditions that hold for hydrodynamical equations it is indeed possible to make computations using large steps in the time variable.

2. Hydrodynamical equations with one spatial variable have the form

1. $$\partial s/\partial t + v\,\partial s/\partial x = f\,,$$

2, 3. $$(\partial p/\partial t \pm \rho c\,\partial v/\partial t) + (v \pm c)(\partial p/\partial x \pm \rho c\,\partial v/\partial x) = g_i\,, \quad i = 1, 2\,,$$

where $s = f(p, \rho)$ is the entropy, p is the pressure, ρ is the density, v is the velocity, and $c = \sqrt{5p/3\rho}$ is the speed of sound.

These equations include three velocities: v, $v + c$, $v - c$. These are velocities at which the invariants $\mathrm{d}s$, $\mathrm{d}p \pm \rho c\,\mathrm{d}v$ are transferred.

The characteristic feature of these velocities is that two of them, v and $v + c$, are positive, and the third, $v - c$, changes from negative to positive in the transition from the subsonic to the supersonic region. To put it crudely, computations will be stable if the ratio of computation steps satisfies inequalities

$$\text{(x)} \qquad \Delta t/\Delta x < 1/(v + c)\,, \qquad \Delta t/\Delta x < 1/(v - c)\,.$$

We will immediately emphasize that these inequalities by no means represent sufficient conditions. The difference scheme itself must satisfy certain algebraic conditions. The conditions (x) vary from point to point and, furthermore, $1/(v + c) \leqslant 1/(v - c)$. Typically, we need to take $\Delta t/\Delta x$ less than the minimum value $1/(v + c)$ in the entire domain. This reduction in the ratio of steps slows down the computations greatly and additionally increases inaccuracies of computations. We can, however, proceed differently. One of the characteristics is vertical at a point $v = c$. Using this characteristic, we can compute the corresponding invariant $\mathrm{d}p - \rho c\,\mathrm{d}v \approx \Delta p - \rho c\Delta v$, where the symbol Δ denotes the increment in the variable t. The difference equation makes it possible, moving

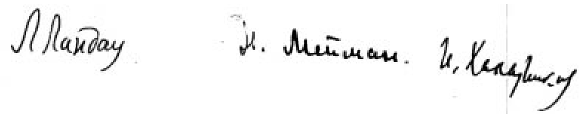
leftward from point to point, to determine the values of $\Delta p - \rho c\Delta v$ at every node in the subsonic region. Since $v - c$ is negative in this region, there exist schemes at which this computation to the left is stable with regard to the variable x. Knowing $p - \rho cv$ at the moment t and $\Delta \rho - \rho c\Delta v$, we obtain the values of $p - \rho cv$ at the moment $t + \Delta t$. Knowing $p - \rho cv$ at a boundary point, we can use boundary conditions to compute $\Delta p + \rho c\Delta v$ and Δs at the boundary at a moment t. Moving rightward from point to point we can achieve stable computations in x owing to the positiveness of v and $v + c$, and find $\Delta p + \rho c\Delta v$ and Δs at grid nodes. Finally, since $v - c$ is positive to the right of the sonic point, computations to the right of the sonic point can be made stable. As a result, we obtain the values assumed by all functions at a moment $t + \Delta t$ and continue computations starting with these values. Under conventional schemes, at large t we automatically go far into the supersonic region. With the method presented here we go into the supersonic region as far as we need to.

Difference schemes can be concocted in such a way that the described method of computations remains stable regardless of the value of $\Delta t/\Delta x$.

One specific feature of such schemes is that the difference equation contains not one leading term in the time index n but several terms leading in index n. The value of the step in t is determined by the degree to which the coefficients of the equation are uniform in t.

The described process of integration does not contradict the general Courant principle, namely that the domain of dependence of a set of difference equations should not be smaller than the domain of dependence of a set of differential equations, but it uses more flexibly the fact that the Courant coefficient is a variable quantity and has different values for equations 2 and 3.

This method was applied to find the limiting regime when $t \to \infty$ for a certain one-dimensional hydrodynamic problem, which was calculated exactly using a different approach. The obtained solution coincided very well with the test solution.



24-18-11 pp.37-40 mb. 046iz of 12.1.52, executed by Meiman

Appendix 2. Article written by L D Landau: "Atomic energy"

COMMITTEE ON THE INTRODUCTION
OF RADIO AND RADIO BROADCASTING
OF THE USSR COUNCIL OF MINISTERS

ASSISTANCE TO LOCAL RADIO COMMITTEES
Manuscript

MATERIALS OF CENTRAL RADIO BROADCASTING

Professor Lev Davidovich Landau,
Stalin Prize laureate,
Doctor of Physicomathematical Sciences

Atomic energy

Humankind learned of the existence of internal atomic energy only very recently. We can even indicate the date on which it suddenly emerged and surprised physicists. It was exactly half a century ago.

What was physics like at the time?

The French chemistry scientist Lavoisier showed already at the end of the 18th century that all materials in the Nature surrounding us are built of permanent ingredients: simple bodies, elements. Water is composed of oxygen and hydrogen. However, oxygen and hydrogen are not composed of any other substances. They are not decomposable. More than seventy such elements became known by the end of the last century. Physicists knew that all of them are composed of extremely small particles we call atoms. This was established already by the English scientist Dalton. The lightest of them is the hydrogen atom. The heaviest of them — the atom of uranium — is almost 240 times heavier.

When the great Russian chemist Mendeleev arranged elements in the order of the increasing weight of their atoms, he obtained a spectacular table with which he was able to predict the existence of new, unknown elements. These were indeed discovered later.

The place occupied by each element in the table was subsequently found to be even more important than it appeared to Mendeleev. It is known as 'atomic number'.

Hydrogen opens the table and is the number one element. It is followed by helium — the number two element. The last of them, uranium, is number 92 element.

An amazing discovery was made in 1896, which really baffled scientists. The French physicist Henri Becquerel discovered that uranium and all its components emit — without any external cause — radiation invisible to the naked eye. This phenomenon was given the name 'radioactivity' (from the Latin 'radius' for 'ray') and [scientists] began a thorough study of it.

It soon became clear that all of the last nine elements of the periodic system — from number 84 to number 92 — are radioactive.

Radioactive materials require that people handle them with great care. Becquerel for some time kept several grains of radium is his waistcoat pocket; as a result, a sore formed on his chest which required prolonged medical attention. Such is the effect of radioactive rays on live tissues. Later it became clear that radioactivity affects cells and cancerous tumors even more destructively. For this reason, these substances became widespread in medical applications.

The nature of radioactivity was explained by one of the greatest physicists of the 20th century, Ernest Rutherford, in England. He understood that atoms in matter which were considered unchangeable do decay and the rays they emit are fragments flying in all directions. Radium decays into heavy atoms of the radioactive element radon and lighter atoms of helium that fly out with a huge velocity of fifteen thousand kilometers per second; they are known as alpha rays.

Radioactive atoms decay at different rates. Uranium decays extremely slowly: its amount on the Earth will be reduced by half after roughly five billion years. In the two or three billion years that the Earth has existed about one fourth of the available uranium has already decayed. Radium decays much faster. Its amount diminishes by about a factor of two in approximately 1500 years. Clearly, all the radium that ever existed on the Earth disappeared a long time ago, so that radium available now is being recreated all the time in uranium decays. It is not surprising therefore that only about one kilogram of radium has ever been extracted.

When atoms decay they release energy. One kilogram of uranium releases the same amount of energy as we get from fifty tons of coal. It might seem that this is a lot of energy; in fact, it is released over several billion years. Consequently, tons and tons of uranium would not heat even a tiny room. It is easy to calculate that the entire amount of radium accumulated on the Earth would perhaps be sufficient to boil two large kettles in a day. True, they would boil for thousands of years, though this is hardly worth the trouble. It would be a very different matter if radioactive decay could be speeded up. The prospect of replacing one hundred tons of coal with two kilograms of uranium looks very attractive. Alas, all attempts to influence the rate of radioactive decay have proved unsuccessful. It remains constant at an accuracy which is far better then that of the best clock movements.

What are these mysterious atoms which cannot be broken into parts however hard we try, but which, on the other hand, decay into fragments without any obvious reason? Science gives a clear and definite answer to this question. No atom is a continuous entity. An atom resembles the solar system, with a heavy nucleus in the middle and light electrons revolving around it. The nucleus is, of course, only relatively heavy. The heaviest nucleus weighs only a hundred billionth of one gram. Scientists also determined the forces acting between the particles of which an atom is composed. These are the forces of electric attraction and repulsion. The nucleus is charged with positive electricity, and electrons with negative electricity. For this reason, electrons are attracted to the nucleus and are repelled from one another.

This discovery is enormously important. Humankind has at last learned for the first time how matter is constructed. Now that the mechanics of motion of electrons in atoms have been understood, people have learned to recognize the properties of matter — sometimes better than the properties of machines that they themselves designed.

All electrons are absolutely identical. Their number in an atom is dictated by the charge of its nucleus. The electric charge of the nucleus has much greater importance for the properties of the atom than its weight or mass. Two nuclei with identical charge but different masses produce atoms so similar that distinguishing between them is almost impossible. We invariably think that these are atoms of the same element. They are, in fact, not quite the same. We call them isotopes. In addition to ordinary nuclei — protons — hydrogen sometimes contains the tiniest amounts of deuterons, which are twice as heavy. Hydrogen with nuclei that are twice as heavy is known as heavy hydrogen, and the water made of it as heavy water. It constitutes only about one hundredth of one percent of light water and extracting it requires a huge amount of labor. Heavy water boils at 103 degrees; in general, the difference between light and heavy water is very small. We see that in the case of hydrogen one isotope is just a negligible impurity. In other cases, the situation may be very different. For example, one half of the atoms of any amount of chlorine are slightly lighter, and the other half are slightly heavier. Chlorine is a mixture of almost equal amounts of two isotopes.

Radioactivity is the decay of the atomic nucleus, of that tiny particle which resides at the center of every atom. In fact, the nucleus has a complex structure. Heavy nuclei of chemical elements found in the last row of Mendeleev's Periodic Table are unstable and gradually decay one after another.

The large amount of energy released by the decay shows that the interaction between particles inside nuclei is much stronger than the interaction between electrons and the nucleus. This is very natural if we take into account the colossal closeness, the extraordinary compactness of matter inside nuclei. The distance between particles in nuclei is less by a factor of tens of thousands than the distance between the nucleus and the electrons surrounding it.

Physicists do not like to be passive witnesses to what happens in Nature independently of them. They always wish to intervene. Twenty seven years ago Rutherford succeeded in artificially splitting the atomic nucleus. The idea of his experiment was very simple. He irradiated various elements with rays emitted by radioactive elements; in other words, he bombarded them with nuclei of helium atoms acting like bullets that move at fifteen thousand kilometers per second — several thousand times faster than artillery projectiles. When he started bombarding nitrogen, he at last produced the transmutation of elements. This was the dream of every alchemist and had come to be regarded as absolutely impossible for nearly a century and a half. The bombarded nucleus of nitrogen absorbed an alpha particle and immediately ejected a proton. Nitrogen was replaced with oxygen that had nothing in common with it. Nitrogen and helium were thus transformed into oxygen and hydrogen.

People produced their first nuclear reaction a mere quarter of a century ago. By now their number has grown to many hundreds. The techniques for achieving these have grown enormously, though. There is no need now to stick to alpha particles emitted by radioactive substances. Physicists now possess more convenient machine guns which send many more bullets moving at much higher velocities. Many different tools allow this. One of them, the cyclotron, generates powerful beams of protons, deuterons or alpha particles whose velocity reaches more than thirty thousand kilometers per second.

Many nuclear reactions release more energy than radioactive decay. Alas this energy cannot be utilized. The difficulty lies in the extremely low efficiency of nuclear reactions. Particles in flight, being charged positively as the nucleus is, are repelled by it. Only if they move very fast can they penetrate the nucleus and produce a reaction. In the meantime, while they are inside matter, they are gradually slowed down and are ultimately unable to overcome the repulsion.

An alpha particle flying through matter is so small and the distances between atoms, nuclei, and the electrons surrounding them are so huge that the probability of an alpha particle hitting a nucleus is extremely doubtful. Just imagine a forest in which each tree stands at a distance of five kilometers from any other tree. Can a projectile hit any tree without us using gun sights? Obviously, in these conditions one nuclear reaction could at best be produced by a million particles. Consequently, the acceleration of a multitude of particles flying in a cyclotron consumes a lot more energy than could be released in a nuclear reaction. The situation looked so hopeless that for a long time physicists treated the prospects of utilizing intranuclear energy just about the same as they treat those of the *perpetuum mobile*.

As it happened, nature was cleverly teasing physicists. New, unexpected phenomena opened up where before everything seemed so clear. Scientists discovered that when the element beryllium is bombarded with alpha particles, its nuclei eject new particles that are electrically neutral. These particles were given the name 'neutrons'. Then it was understood that in fact neutrons together with protons constitute the bricks of which all nuclei of all atoms, and thus all matter, are built. For instance, the deuteron is a combination of one proton and one neutron, helium consists of two protons and two neutrons, etc. The nucleus of uranium is composed of ninety two protons and one hundred forty six neutrons.

The discovery of neutrons constituted a revolution in nuclear artillery. Indeed, as they are not repelled, nothing stops neutrons from penetrating into nuclei. They travel through matter until they enter some nucleus and get stuck in it either because they are absorbed or because they cause a new nuclear reaction. Neutrons invariably cause nuclear transformations without resistance. These are bullets with a spell cast on them; they always find the victim they seek.

Neutrons opened the gates to the enchanted castle where intranuclear energy was hidden. However, an even stronger door, as if iron-clad, waited for us there. When a neutron causes a reaction, a charged proton or an alpha particle is ejected from the nucleus. It would stop inside matter and the reaction would terminate. The hope for success seemed deceptive. Nevertheless, the main thing was accomplished: the idea of the accessibility of atomic energy began to take root.

Seven years ago the news was published that the nucleus of uranium does not throw out, as usual, a proton or an alpha particle but breaks into two fragments. This new type of nuclear reaction is known as fission.

It might seem that nothing of special importance had happened. In reality, though, fission proved to be the magic key that opened the last door behind which internuclear energy was locked. Uranium, a heavy dark-gray metal known for nearly a hundred years, appeared to be the very philosopher's stone for which alchemists had been searching for so long, yet had failed to find. The secret lay not in the fact that fission produces ten times more energy than an ordinary nuclear reaction. It was discovered that from two to three new neutrons are emitted from the nucleus when it undergoes fission. Neutrons, thus, do not perish but reappear, and their number doubles, so that they again penetrate neighboring nuclei of uranium and split them into fragments; the process is thus self-sustained and continues to unfold more and more strongly. Physicists were stunned by this behavior. The cage door flew open and released the beast whose terrible power was known to us quite well.

However, difficulties started to emerge right away. Natural uranium consists mostly of the isotope with atomic weight 238, plus a negligible admixture of the isotope-235. Uranium-235 was found to undergo fission without a hitch by any neutron, while uranium-238 underwent fission only by very fast neutrons. Neutrons moving at a lower speed not only fail to produce fission in uranium-238 nuclei but are simply absorbed into it and drop out of the game. Uranium found in natural conditions is thus unsuitable for fission.

To solve this problem, we need to extract from natural uranium its content of pure uranium-235. This is a very hard task because the difference between the properties of these two isotopes is absolutely minute. However, physicists found methods for separating the two. What was left was to transform laboratory devices into industrial machines. The job fell to physicists of different countries, spurred on by World War II. The scale of this task was grandiose: indeed, American and British experts, in possession of huge technical resources and commanding the services of most physicists from all countries, had to work full-tilt on it for more than four years.

Fascist Germany also tried to solve this problem. Hitler, Germany's bankrupt Fürer, was in a terrible hurry trying to get hold of new weapons of destruction. The Germans failed to implement his goals, and this was the achievement of the Soviet people, who wiped out the fascist beast in its lair and stopped it from making its dreadful last leap. The air forces of the Allies also destroyed quite a few installations on the German territory involved in work on the atomic bomb.

Once a sufficient amount of uranium-235 is accumulated, everything is ready for the reaction. If the amount is too small, neutrons uselessly escape into the air before hitting nuclei. Neutrons are thus unable to multiply and fission has to stop. The required amount of uranium depends on its spatial arrangement. If the entire mass of uranium is shaped into a sphere, only several kilograms of the metal is required.

For an instantaneous explosion, we may, for example, take two pieces of uranium (each too small to cause the explosion) and shoot one of them as a projectile into the other, 'igniting' the explosion by neutrons at the moment of collision.

Comments of compiler

1. K K Omel'chenko, authorized person of the USSR Council of Ministers on the protection of military and state secrets in the media sent the page proofs of L D Landau's article to V A Makhnev in accordance with the agreement reached with V A Makhnev, reference no. 859 of 7 June 1946 (AP RF, F. 93, D. 32/46, L. 116). V A Makhnev in turn arranged with B L Vannikov the delivery of page proofs of this article for approval, reference no. 3/375s of 8 June 1946 (AP RF, F. 93,

D. 32/46, L. 117). V G Levich was assigned to referee the page proofs; his review was published (Appendix 1 to the present letter; see p. 922). A typeset printout of L D Landau's article was returned to K K Omel'chenko on 18 June 1946 by V A Makhnev (AP RF, F. 93, D. 32/46, L. 120).
2. Dated on the basis of the date of the reference number of the document.
3. A search found no page proofs of L D Landau's article. However, the search made it possible to establish that a version of the article from which some data were removed in accordance with the notations of an expert was published in 1946 as a manuscript by the Committee on the Introduction of Radio and Radio Broadcasting of the USSR Council of Ministers (see Appendix 2). After publication was approved on 12 October 1946, a print run of the article (560 copies) was typeset in the typographic works of the Publishing House of Glavsevmorput' (Moscow).

Levich Veniamin Grigor'evich (1917 – 1988), physicist, Corresponding Member of the USSR Academy of Sciences (1958). Worked in the Institute of Physical Chemistry from 1940 until 1958, then in the Institute of Electrochemistry until 1972. Emigrated to Israel in 1978 [*Russian Jewish Encyclopedia* Vol. II (Moscow: RAEN – 'EPOS', 1995)].

The USSR Atomic Project Vol. 2, Book 2, pp. 525 – 530.

References [3]

1. "L.D. Landau: Personal file", Rosatom Archive, Fond 1, Opis' 6pf, Delo 700
2. "USSR Council of Ministers PGU report "On progress in the work on development of the atomic industry" of 25.03.1951" with an Appendix "List of science supervisors of atomic organizations and enterprises and principal directions of research efforts", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 7 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2007) pp. 232 – 267
3. *Geroi Atomnogo Proekta* (Heroes of the Atomic Project) (Sarov: RFYaTs – VNIIEF, 2005)
4. "Osetrov N.A. to Beria L.P. Memorandum proposing to dismiss L.D. Landau from the staff of Laboratory No. 3 of 1.03.1949", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 4 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2003) p. 607
5. "Memorandum from Kurchatov I.V. to Pervukhin M.G. on the need to involve L.D. Landau and P.L. Kapitza in the work on the atomic issues of 20.3.1943", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 1 *Atomnaya Bomba. 1938 – 1945* (Atomic Bomb. 1938 – 1945) Book 1 (Gen. Ed. L D Ryabev, composed by L I Kudinova) (Moscow: Fizmatlit, 1998) p. 325
6. "Letter from I.V. Kurchatov to L.P. Beria concerning scientists whose participation is necessary for the work on the problem of 24.11.1944", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 1 *Atomnaya Bomba. 1938 – 1945* (Atomic Bomb. 1938 – 1945) Book 1 (Gen. Ed. L D Ryabev, composed by L I Kudinova) (Moscow: Fizmatlit, 1998) pp. 162 – 165
7. "Letter from I.V. Kurchatov to L.P. Beria on including L.D. Landau in the work of Laboratory No. 2 of 18.12.1945", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2006) p. 79
8. "Protocol No. 18 of the Technical Council of the USSR CM Special Committee of 18.12.1946", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2006) pp. 93 – 94
9. "Letter from Alikhanov A.I. to Beria L.P. on the need to have L.D. Landau's participation in the theoretical and computational work of Laboratory No. 3 on facility No. 7 of 9.03.1949", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 4 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2003) pp. 605 – 606
10. "Letter from Pervukhin M.G. and Meshik P.Ya. to Beria L.P. on the expedience of subsequent work of L.D. Landau at the Laboratory No. 3 of 29.04.1949", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 4 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2003) p. 652
11. Goncharov G A "The extraordinarily beautiful physical principle of thermonuclear charge design (on the occasion of the 50th anniversary of the test of RDS-37 — the first Soviet two-stage thermonuclear charge)" *Usp. Fiz. Nauk* **175** 1243 (2005) [*Phys. Usp.* **48** 1187 (2005)]
12. Krivonosov Yu I "Landau and Sakharov under KGB surveillance" *Voprosy Istorii Estestvoznaniya Tekhniki* (3) 123 (1993)
13. Ginzburg V L *O nauke, o Sebe i o Drugikh* (About Science, Myself, and Others) 3rd ed. (Moscow: Fizmatlit, 2003) [Translated into English (Bristol: IOP Publ., 2005)]
14. "A Decree of the Presidium of the USSR Supreme Soviet of 29.10.1949 "On awarding Orders of the USSR to scientific, engineering and technical workers for outstanding achievements in fulfilling a special assignment of the government", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 1 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 1999) p. 564
15. "The USSR CM Resolution No. 5070-1944ts/sd "On decoration and payments of bonuses for outstanding scientific discoveries and technological achievements in the utilization of atomic energy" of 29.10.1949", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 1 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 1999) pp. 530 – 562
16. "The USSR CM Resolution No. 21-8-814 "On approving the list of bonus payments in accordance with the USSR CM Resolution No. 5070-1944 of 29 October1949 to scientists, engineers, workers and employees who distinguished themselves in executing special assignments of the Government" of 16.05.1950", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 7 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2007) pp. 49 – 130
17. "The USSR CM Resolution No. 3044-1304ts "On assignment of Stalin Prizes to scientists and engineers from the Ministry of Medium Machine Building and other organizations for the development of the hydrogen bomb and improved designs of the atomic bombs" of 31.12.1953", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 7 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2007) pp. 635 – 642
18. "Decree of the Presidium of the USSR Supreme Soviet of 4.01.1954 "On giving Tamm I.E., Sakharov A.D., Landau L.D. and others the

[3] All archival documents in the bibliographic list have been declassified.

title of a Hero of Socialist Labor'' of 4.01.1954'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 7 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2007) p. 648

19. Goncharov G A, Ryabev L D ''The development of the first Soviet atomic bomb'' *Usp. Fiz. Nauk* **171** 79 (2001) [*Phys. Usp.* **44** 71 (2001)]
20. ''Memorandum from V.A. Malyshev and S.N. Kruglov to G.M. Malenkov on setting up the protection of the leading scientists and specialists executing task orders of the Ministry of Medium Machine Building of 11/12.12.1952'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 5 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2005) p. 800
21. ''The USSR CM Resolution No. 2959-1273ts ''On setting up the protection of the leading scientists and specialists executing task orders of the Ministry of Medium Machine Building'' of 16.12.1953'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 5 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2005) pp. 602 – 603
22. Akhiezer A I, Pomeranchuk I Ya *Vvedenie v Teoriyu Mul'tiplitsiruyushchikh Sistem* (*Reaktorov*) [Introduction to the Theory of Multiplicating Systems (Reactors)] (Eds B L Ioffe, A S Gerasimov) (Moscow: IzdAT, 2002)
23. ''The USSR CM Resolution No. 803-325ts/sd of 9.04.1946 ''On the structure of PGU and establishment of NTS'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 2 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2000) pp. 187 – 201
24. ''Protocol No. 24 of the PGU NTS session of 22.07.1946'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2006) pp. 164 – 168
25. ''Protocol No. 33 of the PGU NTS meeting of 29.08.1946'', Rosatom Archive, F. 2, Op. 2, Delo 33
26. ''Protocol No. 61 of the PGU NTS meeting of 10.02.1947, composing report by L.D. Landau ''Theoretical studies in nuclear physics'', Rosatom Archive, F. 2, Op. 2, Delo 61; in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2006) pp. 225 – 228
27. ''Assignment from M.G. Pervukhin'', Rosatom Archive, F. 2, Op. 2, Delo 18033 (assignments of the NTS), ref. number T-122/34sd of 21.2.1947, folder No. 2
28. ''Protocol No. 77 of the PGU NTS meeting of 2.06.1947'', Rosatom Archive, F. 2, Op. 2, Delo 77
29. ''Protocol No. 89 of the PGU NTS meeting of 25.8.47'', Rosatom Archive, F. 2, Op. 2, Delo 89
30. ''Assignment from B.L. Vannikov of 28.8.1947'', Rosatom Archive, F. 2, Op. 2, Delo 18033, ref. number T-507/13sd, folder No. 21
31. ''Protocol No. 100s of the meeting of the NTS PGU ''On the plan of research at the Institute of Chemical Physics'' of 11.12.1947'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2006) pp. 345 – 350
32. ''Assignment from B.L. Vannikov'', ref. number T-778/13sd of 26.12.1947, Rosatom Archive, F. 2, Delo 18034
33. ''Letter from N.N. Semenov to I.V. Stalin on protection against atomic bombs of 30.06.1947'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2006) pp. 302 – 303
34. ''Protocol No. 104 of the PGU NTS meeting of 13.01.1948 on the discussion of the proposal of Academician Semenov N.N.'', Rosatom Archive, F. 2, Op. 2, Delo 104
35. ''Protocol No. 106 of the PGU NTS meeting of 26.1.1948'', Rosatom Archive, F. 2, Op. 2, Delo 106
36. ''Protocol No. 107s of the PGU NTS meeting of 29.01.1948'', Rosatom Archive, F. 2, Op. 2, Delo 107
37. ''B.S. Pozdnyakov, A.I. Alikhanov, L.D. Landau. Final report ''On the proposal by Academician Semenov N.N. (on using accelerators as means of protection against the action of products)'', in Protocol No. 107 of the PGU NTS meeting of 29.1.1948, Rosatom Archive, F. 2, Op. 2, Delo 107
38. ''NTS final report concerning the proposal of Academician Semenov N.N. of 5.02.1948 (on using accelerators as means of protection against the action of atomic bombs)'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2006) pp. 385 – 389
39. ''Protocol No. 115 of the PGU NTS meeting of 5.4.1948 ''Opinion of a commission of experts composed of N.N. Semenov, I.V. Kurchatov, L.D. Landau, Ya.B. Zel'dovich on the design of heavy-water pile of the Laboratory No. 3 of the AN SSSR'', Rosatom Archive, F. 2, Op. 2, Delo 115
40. ''Letter from Kurchatov I.V. to Vannikov B.L. on involving a group of specialists in the work on thermonuclear reactor'', ref. number 6sd of 04.01.1951, Rosatom Archive, F. 24, Delo 26562, Ll. 3 – 5
41. ''Letter from Vannikov B.L. to Kurchatov I.V. with a permission to involve a group of specialists in the work on thermonuclear reactor'', ref. number 101/25sd of 20.01.1951, Rosatom Archive, F. 24, Delo 26562, L. 2
42. ''Protocol of the session chaired by I.V. Kurchatov ''On considering the results and main directions in the research work at the facility 'M'' of 23.07.1951'', in the protocol No. M-5 of PGU NTS of 5.05.1952, Rosatom Archive, F. 2, Op. 9, Delo 229, Ll. 165 – 170
43. ''Protocol No. M-5 of PGU NTS of 5.05.1952'', Rosatom Archive, F. 2, Op. 9, Delo 229
44. ''Letter from Kurchatov I.V. to Vannikov B.L. on organizing a seminar at the Institute of Chemical Physics of the AN SSSR of 7.12.1946'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2006) pp. 212 – 213
45. ''The USSR CM Resolution No. 2143-565 of 19.06.1947 ''On measures to ensure the launching of work on Object 550'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 1 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 1999) pp. 472 – 477
46. ''The USSR CM Resolution No. 1990-774ts/sd ''On additional task orders to the plan of special research for 1948'' of 10.06.1948'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2006) pp. 448 – 451
47. ''The USSR CM Resolution No. 827-303 of 26.02.1950 (reference in a letter from B.L. Vannikov and A.P. Zavenyagin to L.P. Beria of 15.02.1952)'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 7 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2007) pp. 390 – 391

48. ''Letter from I.V. Kurchatov to V.A. Malyshev on Landau's lectures'', ref. number 3235ts of 2.12.1953, Rosatom Archive, F. 24, Delo 47560, Listy 238–239
49. ''Report by M.O. Kornfeld and D.M. Samoilovich ''Separation of isotopes by rectification'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 1 *Atomnaya Bomba. 1938–1945* (Atomic Bomb. 1938–1945) Book 2 (Gen. Ed. L D Ryabev, composed by L I Kudinova) (Moscow: Izd. MFTI, 2002) pp. 558–564
50. ''L.D. Landau ''Vapor pressure produced by isotopes'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 1 *Atomnaya Bomba. 1938–1954* (Atomic Bomb. 1938–1954) Book 2 (Gen. Ed. L D Ryabev, composed by L I Kudinova) (Moscow: Izd. MFTI, 2002) pp. 565–566
51. ''From memorandum sent by Kurchatov I.V. to Pervukhin M.G. on results of research program'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 1 *Atomnaya Bomba. 1938–1945* (Atomic Bomb. 1938–1945) Book 1 (Gen. Ed. L D Ryabev, composed by L I Kudinova) (Moscow: Fizmatlit, 1998) pp. 360–362
52. ''Letter from Vannikov B.L., Pervukhin M.G. and Kurchatov I.V. to L.P. Beria with a draft of a resolution of the USSR Council of Ministers on the work covering production of heavy water by rectification of liquid hydrogen of 18.06.1946'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 2 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 2000) pp. 530–531
53. Landau L D ''Atomnaya energiya'' (''Atomic energy'') (Moscow: Committee on the Introduction of Radio and Radio Broadcasting of the USSR Council of Ministers, 1946)
54. ''Letter from Vannikov B.L. to Makhnev V.A., the Secretary of Special Committee, on the page proofs of the article ''Atomic energy'' by Landau L.D. accompanied with the review by V.G. Levich of 17.06.1946'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 2 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 2000) p. 523
55. ''The USSR CM Resolution No. 805-327ts ''Issues of USSR AS Laboratory No. 2'' of 09.04.1946'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 1 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 1999) pp. 429–430
56. ''The USSR CM Resolution No. 1286-525ts/sd ''On the plan of promoting the works of KB-11 of USSR AS Laboratory No. 2'' of 21.06.1946'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 1 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 1999) pp. 434–456
57. ''The USSR CM Resolution No. 2557-1069ts ''On the plan of research at the Institute for Physical Problems of the USSR AS and measures to assist the Institute'' of 30.11.1946'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 3 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 2002) pp. 78–83
58. ''The USSR CM Resolution No. 1127-402ts/sd ''On the plan of special research for 1948'' of 6.04.1948'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 3 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 2002) pp. 431–454
59. ''Protocol No. 63 of the session of the USSR CM Special Committee of 05.06.1948'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 1 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 1999) pp. 283–287
60. ''Protocol of the meeting at KB-11 on the issues of RDS-2, RDS-3, RDS-4 and RDS-5 of 9.06.1949'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 2006) pp. 592–594
61. ''Memorandum from B.L. Vannikov and I.V. Kurchatov addressed to L.P. Beria on the results of the meeting at KB-11 on 4–9 June 1949 of 15.06.1949'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 2006) pp. 595–601
62. ''The USSR CM Resolution No. 1989-773ts/sd ''On additional items to the plan of work at KB-11'' of 10.06.1948'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 2006) p. 447
63. ''From the ''Protocol of the meeting on issues of KB-11 with participation of B.L. Vannikov and I.V. Kurchatov, while they visited the Object on 23–28 December 1948'' of 5.01.1949'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 2006) pp. 503–515
64. ''Letter from Yu.B. Khariton to B.L. Vannikov on bonuses for the participants of the work on creation of the A-bomb (manuscript)'', Rosatom Archive, F. 1, Op. 35, Delo 10, ref. number 202sd of 3.03.1949, Ll. 29–35
65. ''Letter from A.P. Aleksandrov to M.G. Pervukhin on deadlines for work on the theory of efficiency of 19.03.1949'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 2006) p. 536
66. ''From the protocol No. T-6 of the meeting of the PGU NTS of 25.04.1949'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 2006) pp. 559–562
67. ''Yu.B. Khariton and K.I. Shchelkin. ''Brief report on the status of work at KB-11 on 15 April 1949'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 2006) pp. 547–550
68. ''Protocol of the meeting of the Laboratory No. 2 NTS on KB-11 issues of 21.12.1948'', Rosatom Archive, F. 24, Delo 16344, ref. number 148/1ts/sd of 21.01.1949, Ll. 113–120
69. ''Materials of the meeting of B.L. Vannikov and I.V. Kurchatov at KB-11 on 4–9.06.1949'', in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945–1954* (Atomic Bomb. 1945–1954) Book 6 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit–Sarov: RFYaTs–VNIIEF, 2006) pp. 576–582
70. ''Protocol of the meeting of the Learned Council on issues of KB-11 on 1–8 February 1951'', ref. number 40/3sd of 9.02.1951, Rosatom Archive, F. 24, Op. 18, Delo 17, Ll. 1–78
71. ''Memorandum from Yu.B. Khariton and Ya.B. Zel'dovich ''On the current status and plan of works on RDS6T'', ref. number 95/

3sd of 29.01.1953, Rosatom Archive, F. 24, Op. 18, Delo 20, Ll. 17 – 22
72. "Letter from Malkov M.L. to Pavlov N.I.", ref. number 471sd of 15.10.51, Rosatom Archive, F. 4, Op. 31, Delo 43, Ll. 31 – 49
73. "L.D. Landau, E.M. Lifshitz, I.M. Khalatnikov, S.P. D'yakov. Report "On the possibility of detonation of deuterium in a tube", appended to the letter of A.P. Aleksandrov to N.I. Pavlov, ref. number 224ts/sd of 3.02.1951, Rosatom Archive, F. 4, Op. 31, Delo 43, Ll. 53 – 73
74. "Meeting on the RDS-6t problems of 8 – 9.01.1952", ref. number 9/74sd of 12.01.1952, Rosatom Archive, F. 24, Op. 18, Delo 11, Ll. 27 – 29
75. "Letter from Malkov M.L. to Zernov P.M.", ref. number 26sd of 17.1.52, Rosatom Archive, F. 24, Op. 18, Delo 11, Ll. 33 – 40
76. "Order No. 135sd from head of PGU A.P. Zavenyagin of 6.04.1953 on setting up a commission on RDS-6T", Rosatom Archive, F. 24, Op. 4, Delo 183, l. 124
77. "Conclusions of the commission on the RDS-6t product of 6.05.1953", Mb. 9/978sd, Rosatom Archive, F. 24, Op. 18, Delo 20, Ll. 103 – 113
78. "Memorandum from A.P. Zavenyagin and I.V. Kurchatov to L.P. Beria", ref. number 959/1ts/sd of 29.5.1953, Rosatom Archive, F. 24, Op. 18, Delo 11, Ll. 114 – 115
79. "Memorandum from B.L. Vannikov to L.P. Beria on the RDS-6t product", ref. number ST-1003sd of 10.06.1953", Rosatom Archive, F. 24, Op. 18, Delo 20, Ll. 136 – 138
80. "The USSR CM Resolution No. 5373-2333ts/sd of 29.12.1951", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 7 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2007) pp. 373 – 379
81. "Zel'dovich's Ya.B. letter (manuscript) to Vannikov B.L. with the conclusions of the commission on RDS-6s of 30.01.1952", entry number 1235/30sd, Rosatom Archive, F. 24, Op. 18, Delo 11, Ll. 56 – 57
82. "Conclusions of the commission on the current status of computational and theoretical work on the RDS-6s product (manuscript)", entry number 1236/30sd, Rosatom Archive, F. 24, Op. 18, Delo 11, Ll. 58 – 63
83. "Letter from B.L. Vannikov, A.P. Zavenyagin, N.I. Pavlov, P.M. Zernov to L.P. Beria on RDS-6s", ref. number 351/1sd of 27.02.1952, Rosatom Archive, F. 24, Op. 18, Delo 11, Ll. 64 – 66
84. "Letter from A.P. Aleksandrov and L .D. Landau to A.P. Zavenyagin on RDS-6", ref. number 0210sd of 13.4.1952, Rosatom Archive, F. 4, Op. 31, Delo 41, Ll. 98 – 99
85. "Letter from L.D. Landau and I.E. Tamm to L.P. Beria on security clearance for N.S. Meiman", ref. number 0230ts/sd of 9/V-52 (copy), entry number SC-5831 of the Special Committee, Rosatom Archive, F. 24, Delo 61464, l. 169
86. "Letter from A.P. Aleksandrov to N.I. Pavlov in regard to N.S. Meiman", ref. number 027ts/sd of 5.05.1952, Rosatom Archive, F. 24, Delo 61464, Ll. 170 – 172
87. "Letter from A.P. Aleksandrov to L.P. Beria in regard to N.S. Meiman", ref. number 0280ts/sd of 9.05.1952, Rosatom Archive, F. 24, Delo 61464, l. 173
88. "Letter from A.P. Zavenyagin, N.I. Pavlov to L.P. Beria", ref. number 999/1ts of 27.05.1952, Rosatom Archive, F. 24, Delo 61464, l. 167
89. "Letter from B.L. Vannikov, A.P. Zavenyagin, I.V. Kurchatov, Yu.B. Khariton, E.P. Slavsky, N.I. Pavlov, P.M. Zernov to L.P. Beria with a draft resolution of the USSR CM concerning RDS-6s", ref. number 842/1sd of 7.05.1952, Rosatom Archive, F. 24, Op. 18, Delo 11, Ll. 133 – 147
90. "L.D. Landau to A.P. Zavenyagin "Report on work progress on MC for July 1952", ref. number 392ts/sd of 28.07.1952, Rosatom Archive, F. 4, Op. 31, Delo 43, l. 101
91. "Letter from Malkov M.L. to A.P. Zavenyagin "Plan of works on MC for the 2nd half of year 1952", Rosatom Archive, F. 4, Op. 31, Delo 43, ref. number 343ts/sd of 3.07.1952., Ll. 18 – 20
92. "Letter from Malkov M.L. to A.P. Zavenyagin with L.D. Landau's report", Rosatom Archive, F. 4, Op. 31, Delo 43, ref. number 495ts/sd of 3.10.1952, Ll. 198 – 199
93. "K.I. Shchelkin. Information sheet of 18.5.1952 "On the work of Academician Landau L.D. on KB-11 issues", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 7 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2007) pp. 429 – 432
94. "Letter from A.P. Aleksandrov to A.P. Zavenyagin involving evaluation of the work of L.D. Landau", Rosatom Archive, F. 24, Delo 61464, ref. number 0260ts/sd of 19.5.1952, Ll. 43 – 51
95. "Memorandum from A.P. Zavenyagin and N.I. Pavlov to L.P. Beria on Landau's work", ref. number 949/1sd of 20.5.1952 (information sheet — Mb. 852sd of 20.5.1952), Rosatom Archive, F. 24, Delo 61464, Ll. 17 – 19
96. "A.D. Sakharov, I.E. Tamm, Ya.B. Zel'dovich description of "Model of the RDS-6S product", mb. 9/206sd of 14.07.1953, Rosatom Archive, F. 24, Op. 18, Delo 20, Ll. 160 – 187
97. Khariton Yu B, Adamskii V B, Smirnov Yu N "On the making of the Soviet hydrogen (thermonuclear) bomb" *Usp. Fiz. Nauk* **166** 201 (1996) [*Phys. Usp.* **39** 185 (1996)]
98. Gurevich I I, Zel'dovich Ya B, Pomeranchuk I Ya, Khariton Yu B "Utilization of nuclear energy of light elements" *Usp. Fiz. Nauk* **161** (5) 171 (1991) [*Sov. Phys. Usp.* **34** 445 (1991)]
99. Goncharov G A "American and Soviet H-bomb development programmes: historical background" *Usp. Fiz. Nauk* **166** 1095 (1996) [*Phys. Usp.* **39** 1033 (1996)]
100. Goncharov G A "On the history of creation of the Soviet hydrogen bomb" *Usp. Fiz. Nauk* **167** 903 (1997) [*Phys. Usp.* **40** 859 (1997)]
101. Adamskii V B, Smirnov Yu N "Once again on the creation of the Soviet hydrogen bomb" *Usp. Fiz. Nauk* **167** 899 (1997) [*Phys. Usp.* **40** 859 (1997)]
102. Romanov Yu A "Memoir of the Teacher" *Usp. Fiz. Nauk* **166** 195 (1996) [*Phys. Usp.* **39** 179 (1996)]
103. Shpinel' V S "Remarks on the paper by G A Goncharov and L D Ryabev "The development of the first Soviet atomic bomb" *Usp. Fiz. Nauk* **172** 235 (2002) [*Phys. Usp.* **45** 227 (2002)]
104. Goncharov G A, Ryabev L D "About V S Shpinel's remarks on the review "The development of the first Soviet atomic bomb" *Usp. Fiz. Nauk* **172** 236 (2002) [*Phys. Usp.* **45** 228 (2002)]
105. Kiselev G V, Konev V N "History of the realization of the thorium regime in the Soviet Atomic Project" *Usp. Fiz. Nauk* **177** 1361 (2007) [*Phys. Usp.* **50** 1259 (2007)]
106. Kiselev G V "Moscow State University physics alumni and the Soviet Atomic Project" *Usp. Fiz. Nauk* **175** 1343 (2005) [*Phys. Usp.* **48** 1251 (2005)]
107. "Information sheet of A.I. Akhiezer and I.Ya. Pomeranchuk about the book on the theory of atomic reactors of 30.10.1948", in *Atomnyi Proekt SSSR. Dokumenty i Materialy* (The USSR Atomic Project. Documents and Materials) Vol. 2 *Atomnaya Bomba. 1945 – 1954* (Atomic Bomb. 1945 – 1954) Book 4 (Gen. Ed. L D Ryabev, composed by G A Goncharov) (Moscow: Fizmatlit – Sarov: RFYaTs – VNIIEF, 2003) pp. 547 – 548