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The Germans and the Development of Rocket Engines in the USSR

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Previous analyses of post-World War II developments of German rocket engines in Russia were mainly based on information published by Soviet scientists and design engineers in obscure specialist journals, which were the only sources giving the technical parameters of these engines. No detailed drawings and few photographs were published.

A more accurate picture of the genesis of post-war Soviet rocket propulsion can now be painted. The author was granted unprecedented access to the archives of Moscow enterprises and research facilities. This material is supplemented by that from new Russian publications in the nineties and personal interviews with the German rocket experts who were taken to the USSR. For the first time it became clear that the *raketnyje dvigateli* (rocket engines) of even today's Soyuz launcher are based on the basic developments of German experts.

Keywords: German rocket engines, German rocket experts, Soviet rocket genesis

1. From the A4 'Basket Head' Chamber Model 39 to the RD-100

As soon as the Red Army occupied Thuringia in July 1945, the resurrection of the extremely expensive Aggregat 4/Vergeltungswaffe 2 engine began. The background is generally known: after a long test series, a reliable 1.5-tonne thrust liquid rocket engine combustion chamber was produced by Dr.-Ing. Walter Thiel, Director of the Engine Development Department of the Heeresversuchsanstalt (Military Research Institute) in Peenemuende. Reliable combustion in larger chambers proved difficult to achieve. Tests using three of the 1.5 tonne chambers as preburners together with a combustion products mixing chamber produced the best results. For the prototype A4 engine eighteen of these 1.5 tonne preburners were arranged around a spherical mixing chamber (the basket-shaped combustion chamber head). But wartime restrictions on experts and material required that the series production engine be made simpler. Particularly the use of 18 preburners (wartime German name: Vorkammer, Russian: forkamera) was very overly complex and resulted in complicated and confusing propellant flow diagrams [1 and 2].

Rocket engine development had been delegated to German universities since the late 1930's. The (then) Technical University in Dresden took the lead. Certain staff members of the Mechanical Laboratory under Professor Georg Beck (1901 – 1943) were considered indispensable. Among the most inventive of the engine group were Dr. Karl Zinner (inventor of the shower-head injector); engineers Hans Lindenberg ('Papa' Lindenberg; died in 1947 in the United States), and Konrad K. Dannenberg. They were sent to Peenemuende and were constantly present at test stand V in Kummersdorf [3 and 4].

The test and examination of new injector orifice patterns was a long trial-and-error process. It became clear that it would take a very long time to eliminate the characteristic whining and booming caused by the resonance and vibration phenomena during combustion, which caused injector face erosion and burn-through. Only when these problems were solved could a start be made on production of a truly feasible production engine for the V2.

The only thermally stable injector that was ready for production was the shower-head injector plate B7 for the JATO 4.2 t engine and B8 for the Wasserfall air defence rocket with eight tonnes of thrust [5].

By 1942 the final A4 engine configuration had to be frozen for production to meet the huge war demand. The 18 preburners were retained, but a lightweight nozzle throat was developed (using film cooling and glass wool insulation instead of double-walled regenerative liquid cooling). The screw-on aluminium head was replaced by a welded steel

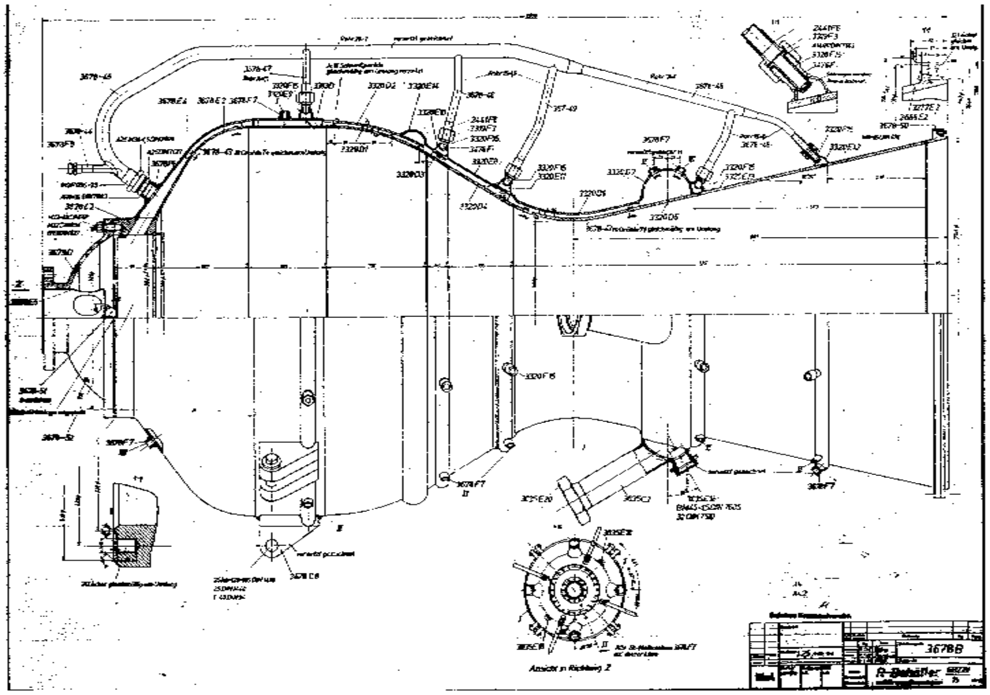

Fig. 1 Cone head oven 39a for the centrally located injecting mix hole plate B8. This engine was to drive the A4/series C. (© German Museum/Munich)

head [4]. This engine was used in the A4/series B and in the production retaliatory missile V2 [6].

By the end of the war the Dresden team had developed the large centrally-mounted injector plate of 350 mm diameter intended for use in the model 39a tapered head combustion chamber engine for the A4/series C. The injector featured a circular slotted plate with orifice holes arranged in complex radial, parallel and circular patterns [7]. This never went into production, but formed the basis for successful post-war American and French rocket engines. And in the Soviet Union?

When the Russians occupied German territories they discovered a treasure trove of rocket technology in Central Germany. At first the Russians were shocked at the huge dimensions of the A4 engine, but then fell in love with this German 'monster' [8]. By August 1945 Russian-supervised test firings of A4 engines began in the Lehesten slate quarry. Train wagons with more than 50 engines had been discovered, allowing a Soviet-German test team under Arwid Pallo to run a thorough test engine optimisation programme. This included computation and selection of the cross-sectional area in the propellant feed lines and the measurement of the duct flow capacity for both propellants [9].

In October V. P. Glushko took over the Oertelsbruch facility. He was farsighted enough to see the potential of this huge engine and formed an

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Mischdüsen-Untersuchungen am 1to-Behälter

1. Abschließende Untersuchungen an der Parallelzellendüse.
2. Entwicklung der Radialzellendüse.
3. Versuche mit der Kreiszellendüse.

Dresden, den 1. Dezember 1941.

Fig. 2 Cover illustration of the summarising report on injecting mix hole investigations, TH Dresden. (© German Museum/ Munich)

engineering department to exploit it. It has been repeatedly alleged that the later Soviet R-1 and its components were only simplified copies of the A4. This was not the case; Glushko's Plant IV within the

Nordhausen Central Works was carrying out further development work which laid the foundation of a whole Soviet engine series [10].

Willi Schwarz was appointed German head of the test stand. He had been responsible for the six big Peenemuende test stands and had since November 1943 co-ordinated construction of the engine plants near Saalfeld [11]. Werner Baum was made head of the related engineering department in Nordhausen for the computation and design of the A4 engine system. He had been the controlling engineer for the complete A4 missile at the Heereswaffenamt (Armed Forces' Weapons Office). Baum and his team now rewrote summary reports on the swirl, splash, and shower-head injector plates; the steam-generators using solid and liquid catalysts; etc.

Engines were consumed at a rapid rate in the tests. The last big test series between July and September 1946 comprised more than 40 engine runs with slightly modified injector systems and varied injection parameters. It became obvious that the thrust of the A4 engine could be increased from 25 to 35 tonnes without great technical changes. The test results and modifications required were documented in 22 thick files [12]. Yet even the best of the modified engines did not show improvement in the degree of engine chamber erosion. But the team was fired by ambition – they knew they could achieve more. Did they intend to show their German colleagues that as much could be achieved by the Russians as by the Americans or French?

Suddenly everything stopped. On October 22, 1946 more than 2100 experts were deported to the Soviet Union, including a group of 308 experts in propulsion technology. Baum, Schwarz and 22 other staff members ended up in Khimki, a suburb in the north-west of Moscow, at factory no. 456, under the jurisdiction of the Ministry for the Aviation Industry [13 and 14]. Head of this engine shop, called OKB-GDL (now NPO Energomash): V. P. Glushko.

The Germans' first task in Khimki was to select, from among those shipped, the best German A4 engines for launches and static tests at the new Kapustin Yar range. This was located on the Volga River, and tests were to begin in 1947. Due to lack of instrumentation, for calibration purposes nominal settings had to be used for the steam generator, the turbopump, the propellant ducts, and the combustion chamber. With the pre-set values the acceptable range of combustion chamber pressure

Fig. 3 Willi Schwarz: Got vocational training as a metal worker in the Breslau shipyard and prepared himself in evening classes for a study. Between 1929 and 1931 he was a sailor and got into close contact with boiler steam engines and turbines. He completed his engineering studies at the Höhere Technische Staatslehranstalt for Mechanical Engineering in Breslau in 1934. After he had worked in several enterprises he was employed at the Armed Forces Headquarters (Oberkommando des Heeres) as test engineer for the rocket engine test benches in Kummersdorf, Peenemuende and Lehesten in 1938.

Fig. 4 Werner Baum: After he had attended the Oberrealschule (secondary school) and had completed a period of industrial practical work he got a training as an arms engineer at the Heeresfachschule (Armed Forces Technical College) in Berlin. Being the controlling engineer for the overall device A4 he was responsible for the controlling departments in the Mittelwerk, the test fields in Lehesten, Ober-Raderach, Attnag-Puchheim. After World War II he changed from the Electromechanical Plant in Peenemuende to the Zentralwerke Nordhausen in February 1946.

TABLE 1: *Group of German Experts in Khimki.* (© Olaf Przybilski)

Name, First Name	Title/Profession	Born	Function in Khimki
Baum, Werner	Engineer	04/11/1918	Deputy of the Chief and Technical Designer; Dept. 61
Bönisch, Friedrich	Engineer	18/02/1902	Manufact.; Dept. 61/Shop 55
Brötler, Hugo	Welding Engineer	09/11/1898	Oxygen Plant; Shop 55
Chwalczyk, Rudolf	Engineer	10/05/1908	Manufact.; Shop 55
Drews, Erich	Copper Smith	06/03/1912	Manufact.; Dept. Laboratory
Eiseler, Hans	Dipl.-Ing.	08/10/1913	Eng.&Design; Dept. 61
Gerhardt, Bernhardt	Engineer	17/12/1893	Eng.&Design; Dept. 61
Grevesmühl, Alfred	Director	10/08/1902	Manufact.; Dept. 61/Shop 55
Haase, Heinz	Dipl.-Ing.	08/01/1910	Deputy Oxygen Plant; Laboratory Department
Henning, Bruno	Engineer	05/03/1908	Eng.&Design; Dept. 61
Klippel, Alfred	Engineer	26/08/1917	Circuit Electricity; Shop 55
Knack, Wilhelm	Engineer	13/07/1903	Manufact.; Dept. 61/Shop 55
Knittel, Heinz	Precision Mechanic	22/10/1919	Test Bench; Laboratory Department
Leihfeld, Ludwig	Engineer	08/01/1898	Oxygen Plant; Dept. 61/ Laboratory
Meier, Otto	Engineer	24/07/1918	Oxygen Plant; Laboratory Department
Neumeister, Lisa	Housewife	13/09/1920	Translator
Pilz, Arthur	Master	08/06/1912	Test Bench; Laboratory Department
Putze, Oswald	Dr.-Ing.	28/08/1900	Manufact.; Dept. 61/Shop 55
Reinhard, Siegfried	Designer	11/02/1919	Eng.&Design; Dept. 61
Schierhorn, Walter	Welding Engineer	22/02/1907	Manufact.; Shop 55
Schwarz, Willi	Test Engineer	19/11/1910	Deputy of the Test Bench Chief;Laboratory Department
Tannhäuser, Rosemarie	Secretary	05/01/1919	Secretary; Dept. 61/Shop 55
Tschechner, Robert		1899	Manufacture; Laboratory Department
Winskowski, Henrik	Design Engineer	1906	Eng.&Design; Dept. 61

Notes: Engineer (Graduated from Technical College), Dipl.-Ing. (Engineer with University Diploma).

was between 13.6 and 16.6 atm (1.36 and 1.66 Mpa). Based on the measured propellant flow, the chamber pressure would be calculated for the desired propellant flow rate of 125 kg/s. Given the measured performance of the turbomachinery and the steam generator, the overall engine settings could be determined. "They were careful to leave this tricky work to us for those engines to be used in Russian flight tests", Baum observed. Ground runs showed only slight deviations from the nominal values. The eleven launches of the A4 on the river Volga were completed without complication as far as the engines were concerned.

Glushko realised that a technological drawback existed in the test sequence of the German propulsion system. Wartime production and testing of the combustion chamber, the turbopump and the steam generator had been decentralised. After the calibration and the assembly of the propellant ducting they were assembled and were subjected to dry-tests only. Due to the wartime fuel shortage hot-firing tests were carried out on only a sample of the production engines. When launched they were temperamental and achieved varying ranges due to differing engine parameters. When Glushko copied the Model 39 engine for the RD-100 he avoided these problems by fully testing production engines. But this was not the only change he made.

As far as the engine's main characteristics, dimensions and materials, Glushko's team based their work on that of the German experts. They had to transfer the German DIN standards for the materials into Russian GOST standards. Baum and his staff had some years of test experience that was exploited for the RD-100. This allowed optimisation of the turbopump cycle and simplification of the connections between the major structural components; but their work on the oxygen injector was the most decisive change.

This brass component was designed in the thirties by the brilliant inventor Arthur Rudolph. It was the beginning of the triumphant advance of the self-impingement method to obtain fine spraying and mixing of propellants. Injector orifices in Peenemuende and Khimki did not differ from each other in configuration or number of rows and holes [15 and 16]. However, greater attention was paid to the more regular distribution of the oxygen spray in the RD-100. In the Peenemuende design the holes of the first row of the oxygen injector were machined into a 60 mm hexagonal fitting and ran orthogonal from the six sides into the chamber in groups of three. The Khimki experts added an external circular groove at the position of the first row, such that spray from these orifices, like those of the other six rows, would meet at the centre of the oxygen injector.

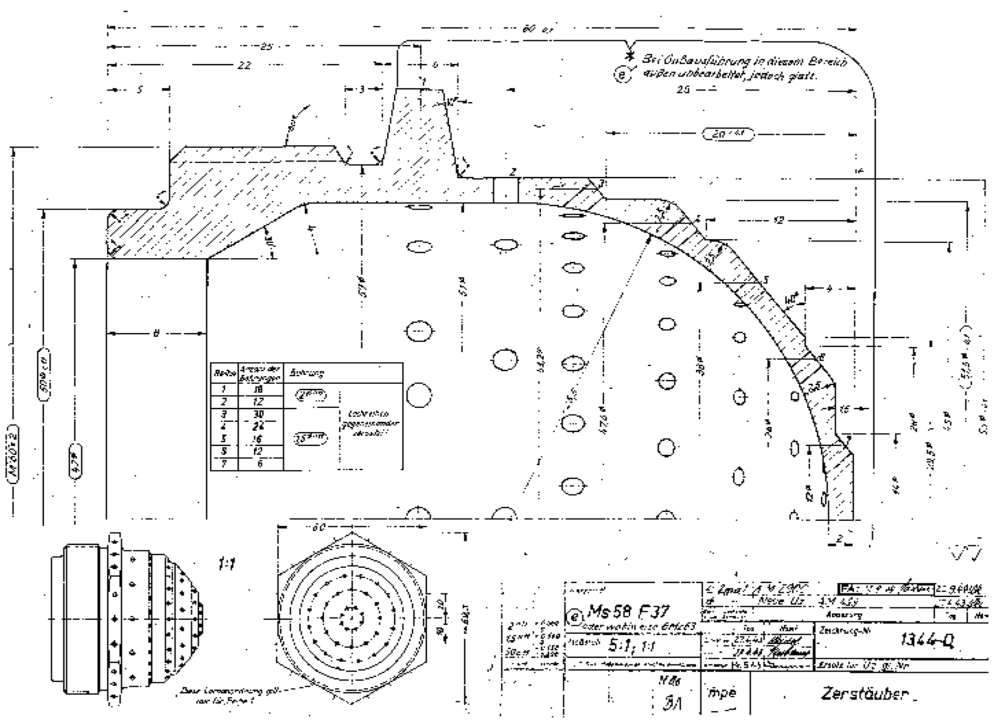


Fig. 5 An original drawing of the atomiser made in Peenemuende.

Количество и размеры отверстий в распылителе окислителя

Ряд	Количество отверстий	Диаметр отверстий, мм	Примечание
1	18	$2A_4$	
2	12		
3	30	$1{,}5^{+0{,}09}$	Отверстия в рядах равнорасположены по окружности
4	24		
5	16		
6	12		
7	8		

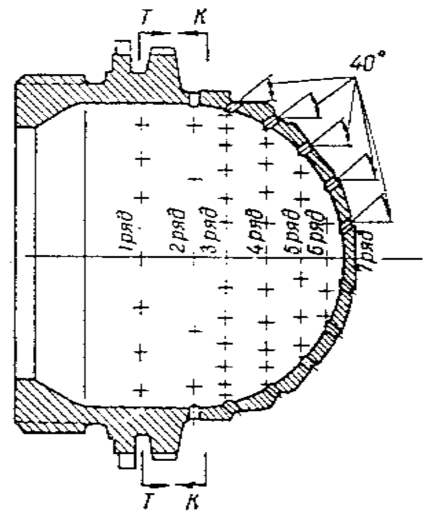


Fig. 6 The oxygen atomiser taken from a Russian design draft. The comparison with the German original in the table illustrates that the drilling dimensions were exactly the same. The sectional drawing shows that there are differences in the contour.

In addition, the narrow labyrinth seal of the oxygen injector was replaced by a broad flat one to prevent it from loosening in the thread. A safety bolt was added which kept the oxygen injector in the holder in the presence of excessive heat and vibration.

The operational parameters of this design were already better than those of the Aggregat 4-B series. It was certainly not ‘a simplified copy’ - more properly an advanced version (see the comparison of operating parameters)! Glushko’s Russians fully exploited the knowledge of the German rocket engine experts in producing an improved version of the A4 engine built from domestically available material.

On September 17, 1948 the first R-1 was launched. As far as the RD-100 engine was concerned it was an instant success.

2. 50 Tonnes Vacuum Thrust!

With the completion of the reconstruction of the RD-100 design, a new phase of work began. The twenty Germans were integrated into a special con-

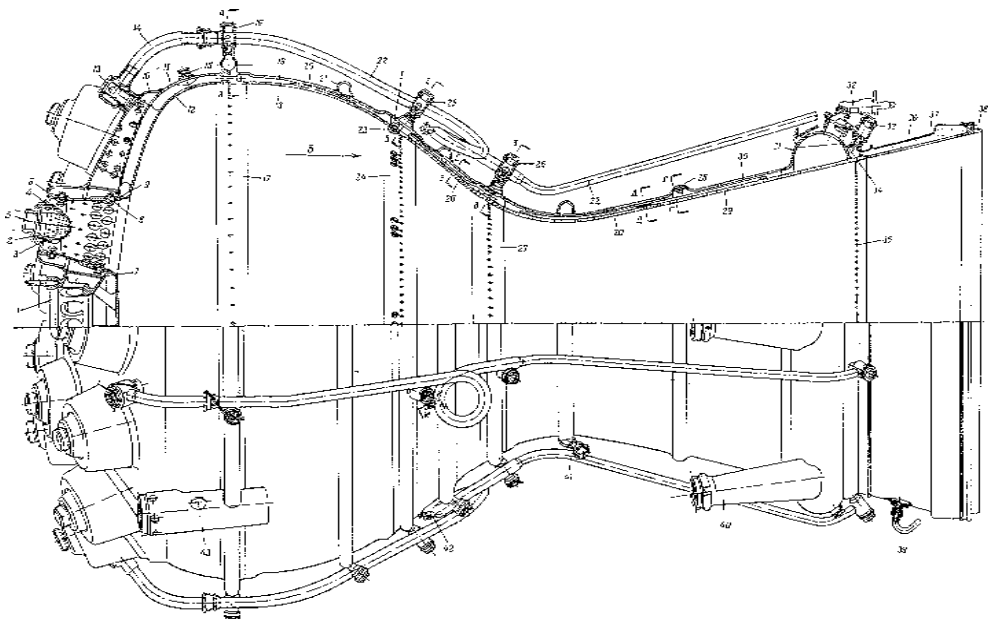


Fig. 7 Sectional view of the combustion chamber of the RD-100. It shows striking resemblance with the A4 engine at first glance.

struction bureau, where they worked very closely together with 80 Russian technicians. The leading engineers under Glushko were Vitka for design, Artamanov for development, and Sebrukh for test. Group leaders under Vitka were Shelyukhin for calculations, Agafanov for the assembly, and List for the combustion chamber. These assignments followed those from the days at Nordhausen.

TABLE 2: *Comparison of Operating Parameters.*

Parameter	A4 Model 39	RD-100
Alcohol Consumption (kg/s)	58	57.8
Oxygen Consumption (kg/s)	72	74
Propellant Pressure:		
- Alcohol, in Combustion Chamber, (Mpa)	1.93	2.02
- Oxygen, in Combustion Chamber, (Mpa)	1.93	2.04
Combustion Chamber Pressure (Mpa)	1.48	1.62
Combustion Chamber Temperature (°C)	2000	2300
Exhaust Velocity (m/s)	2000	2130
Thrust (kN)	257	267
	(at 1,8 km altitude)	(ground level)

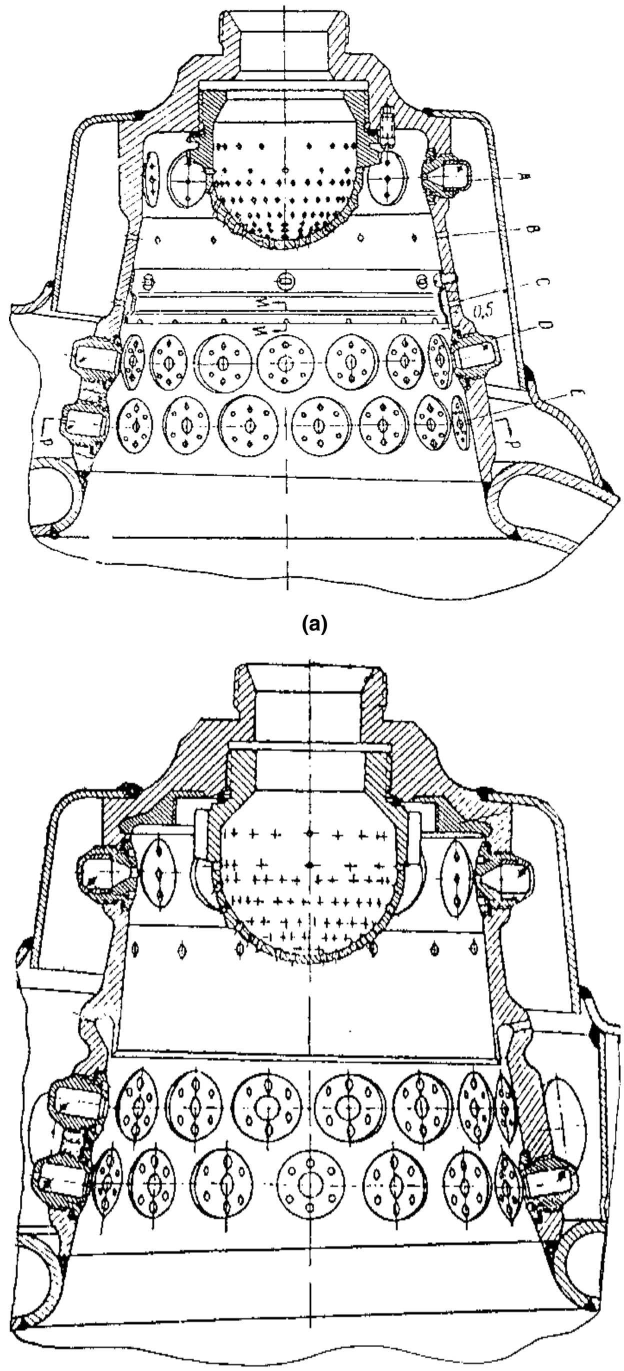
Korolev's first step in further development of the A4 did not entail a noticeable increase in the length of the rocket. He rather chose to improve the operational aspects of the missile, and reduce the size of the entire engine compartment by shortening the engine by 600 mm within the same overall diameter. The means of doing this were formulated together with Glushko in a single meeting: radical shortening and modification of the propellant lines (especially the LOX main line); a toroidal tank for the hydrogen peroxide; a solid propellant gas generator using silver or nickel-based catalysts; a central mixing nozzle; and improved cooling of the combustion chamber. With a more concentrated fuel (85 to 95% ethyl alcohol) the sea level thrust of the engine could be increased from 35 to 40 tonnes. Glushko ordered that the following project phase include a parallel development track with a better long-term solution. So while the first track would involve optimisation of the type 39 chamber to the limits of its performance, the second track would pursue development of a new method of propellant injection and mixing. During the war Germany had pursued development of a single central mixing head. This was designated B8 and was planned for use in the conical head chamber 39a for A4 production series C. This work would be continued in parallel with, and in preference to, improvement of the old chamber design. Further modification of the existing chamber was cancelled as only wasting time.

The objective was clear to both Glushko and the Germans: liquid rocket engines with alcohol fuel had limited specific impulse and did not allow the higher pressures and temperatures necessary for substantial performance improvement. The German combustion chamber model consisted of two steel shells, the chamber wall and the outer hull. These were welded together one within the other, over a single stiffening ring. In between the fuel circulated as a cooling medium. The chamber wall had to be up to 5 mm thick for safety reasons, resulting in a massive 427 kg combustion chamber. With forced improvement of the

combustion chambers (inner pressure 60 kp/cm²; combustion temperature over 3000° C), the desired safety margins could not be reconciled with the capacity of the chamber cooling system. This was only the first problem facing the Germans in the projected improvements of the -100 series engines.

The target was an optimum sea level thrust of 40 tonnes. With less water content in the alcohol, the cooling capacity was reduced, and the temperature of the inner wall increased. Another problem was preventing coking of the brass fuel injector nozzles. Intuition, together with experience, resulted in success: a standard RD-100 combustion chamber was rebuilt with a preburner of special design that could use variable alcohol concentrations. Experience with the Dresden split nozzle injector led to the use of full curtain cooling. Here the radial single-bore nozzles of the model 39 chamber were uncovered. An impingement diaphragm was placed before the nozzle as a distribution splitter, so that the streams were atomised into nearly perpendicularly guided streams. The fuel was directly constrained to the inner chamber wall. In this way the cooling was so improved that up to 92% alcohol could be used as fuel. This was seen as the maximum concentration allowable, provided this form of ring cooling was used for the entire combustion chamber.

Higher temperatures, pressures, and thrusts would require a radical rework of the entire chamber. The chamber throat would have to be insulated with glass wool. The differential pressure between the engine mouth and the external atmosphere would have to be increased. The resulting increased propellant consumption would require a higher injection pressure with a larger chamber diameter. The oxygen injector would have to be completely redesigned. The heavier load on the chamber wall would have to be offset by use of a higher strength steel - requiring a new type of welding.



(a)

(b)

Fig. 8 The preliminary work to increase the engine thrust began in the preburners. Here one can see the greatest differences: to achieve a higherpressure the mass flow of the propellants had to be increased, resulting in a greater number of drilled holes in the oxygen atomiser: a: in the RD-101 versus b: in the RD-103.

The realisation of the German designs under the leadership of Werner Baum brought Glushko's team to the point where they met the requirements of Korolev's rocket. The German team was however unaware of this. After the release of production drawings and test series requirements the Germans were left in the dark as to what would be done with the materials. They were left in the same status as the other 'exile Germans' in other technical areas: required to respond to even the most insignificant inquiries, without questions in response being allowed or answered. The final result was the understanding that the Russians only wanted to be instructed in the technology and that all of the work of the German teams had been 'sent to archives'. This remains to this day a great and continuing error in space history...

Baum's recollection was that the engine designations in the Russo-German project section were different from those known today:

RD-100: A4 engine built in Germany or the Soviet Union using German-fabricated detail parts;

RD-101: A4 engine built from Russian-fabricated parts;

RD-102: Improved curtain cooling, regenerative cooled chamber end, changes to the oxygen shower head, toroidal hydrogen peroxide tank, shortened thrust frame, 75% alcohol fuel;

RD-103: Central mixing nozzle, 4 additional fuel lines in the ring assembly, further shortened thrust frame, 90% alcohol.

The German proposals led to phased progress in Soviet engine technology and met the requirements of chief rocket designer Korolev. By 1949 the entire engine assembly for the R-2 rocket had a length of only 3.35 m, used 92% alcohol fuel, and introduced a silver-based solid catalyst with a toroidal tank for the hydrogen peroxide [17].

The 1950's brought uncertain political support for further development of military ballistic rockets. After the cancellation of development of the R-3 came the edict to 'think intercontinental'. The R-7 was seen as the Soviet answer to the threat of the American bomber fleet. This decision made it necessary to produce an intermediate substitute. The solution was the R-5, a further stretch of the A4, for which the Germans had already delivered the engine design. This was the RD-103 with a German layout: 3.12 m long; a combustion chamber extended to 1819 mm with an 810 mm nozzle opening; and an optimised gas generator with two catalyst packets arranged symmetrically around the hydrogen peroxide line. It delivered a nominal vacuum thrust of

TABLE 3: *Comparison of Engine Parameters.*

Engine	RD-101	RD-103
Fuel consumption (kg/s)	70.6	80.5
Oxidiser Consumption (kg/s)	102.3	115.9
Inner Chamber Pressure (MPa)	2.16	2.44
Specific impulse (sea level) (s)	214	244
Specific impulse (vacuum)(s)	240	251
Pressure of Injection into Chamber (MPa)		
Fuel (Alcohol)	2.6	2.9
Oxidiser (Oxygen)	2.5	3.5
Minimum nozzle diameter (mm)	400	400
Nozzle mouth diameter (mm)	740	810
Thrust at sea level (kN)	363	432
Thrust in vacuum (kN)	402	500

50 tonnes, double that of the original 1939 chamber from which it was derived.

But this was the limit. Within the unbelievably short development period of five years the Germans in the USSR had produced a complete redesign of the rocket's propulsion section, including fundamental design solutions still used today. This design was limited by the knowledge and experience of those that had defined the rocket in Germany. Some details were forgotten or intentionally not disclosed to the Soviets. Take for example, the 'Assembled Works of the Research Projects of the University in the Engine Area', a key document from the Peenemuende Army Proving ground, dated 3 July 1943 [18]. This summarised the fundamental research areas. After the second World War the allies seized and distributed this document worldwide. On page 8a one discovers that Professor

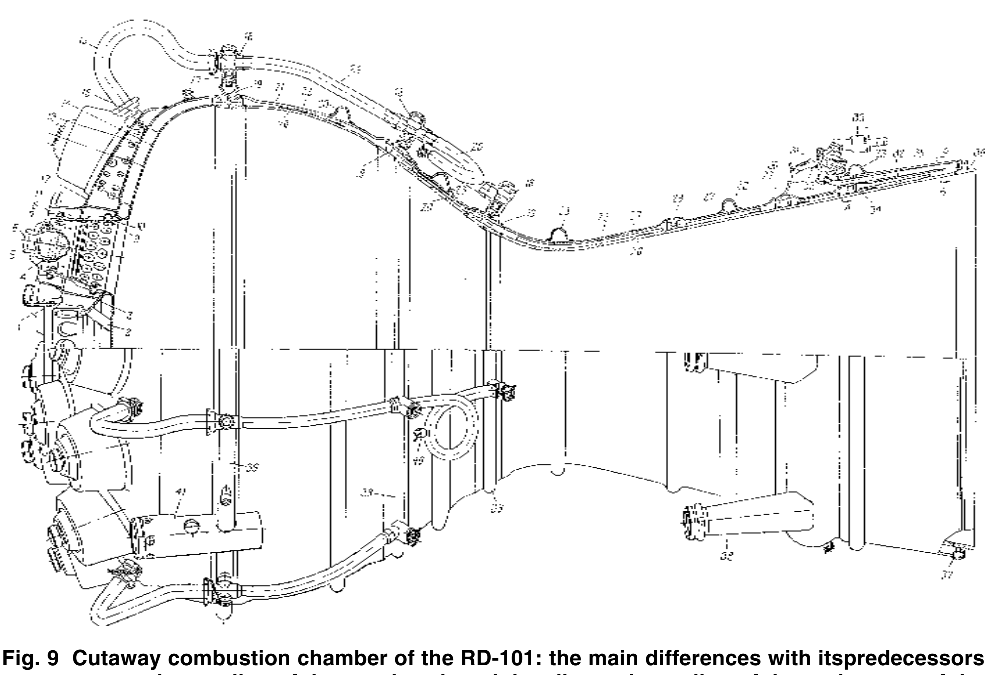


Fig. 9 Cutaway combustion chamber of the RD-101: the main differences with itspredecessors were regenerative cooling of the nozzle exit and the slitcurtain cooling of the preburners of the combustion chamber.

Fig. 10 The RD-101 steam generator with its solid catalyst - a cutaway demonstration model.

Wagner of the Technical University Darmstadt, Institute for Inorganic and Physical Chemistry, conducted research with metal catalysts, such as silver salts, for ignition of T-Stoff (hydrogen peroxide).

3. A 'Liliput' is Born

The Germans at Khimki were required to fulfil yet a second task. Proposals for further engine development required performance parameters that could only be achieved by a radical leap in combustion chamber technology and an improved regenerative cooling system. All this had to be achieved only in a chamber with 25 tonnes thrust. Glushko did not want just an equivalent to the RD-100 - his ultimate objective was engines of 120 and 250 tonnes thrust. He had read documents in the Peenemuende archives that pointed the way to achieving this. He was particularly impressed by Dr. Thiel's intuitive 1939 solution - the 'basket head' chamber 39 consisting of 18 previously developed 1.5 tonne thrust preburning chambers [1]. An alternate variant used 6 x 4.2 tonne thrust drilled mixing plates developed for JATO engines [19]. Glushko, showing his excellent engineering understanding, set the following work objectives:

1) Development of a standard mixing nozzle, that allowed for modular multiple arrangements allowing easier increases in thrust;
2) Use of these nozzles in injector plates of various thrusts; development of the required test combustion chamber;
3) Design of engines of 120 and 250 tonnes through employment of multiples of these injector plates.

This was a hard nut for the Germans to crack, although the knowledge gained in Germany would be helpful. Work on the cooling blanket was especially intensive. The key was a new profile that had been developed at the University of Leipzig [18]. At the beginning of the 1940's Dr Schiller at the Phys-

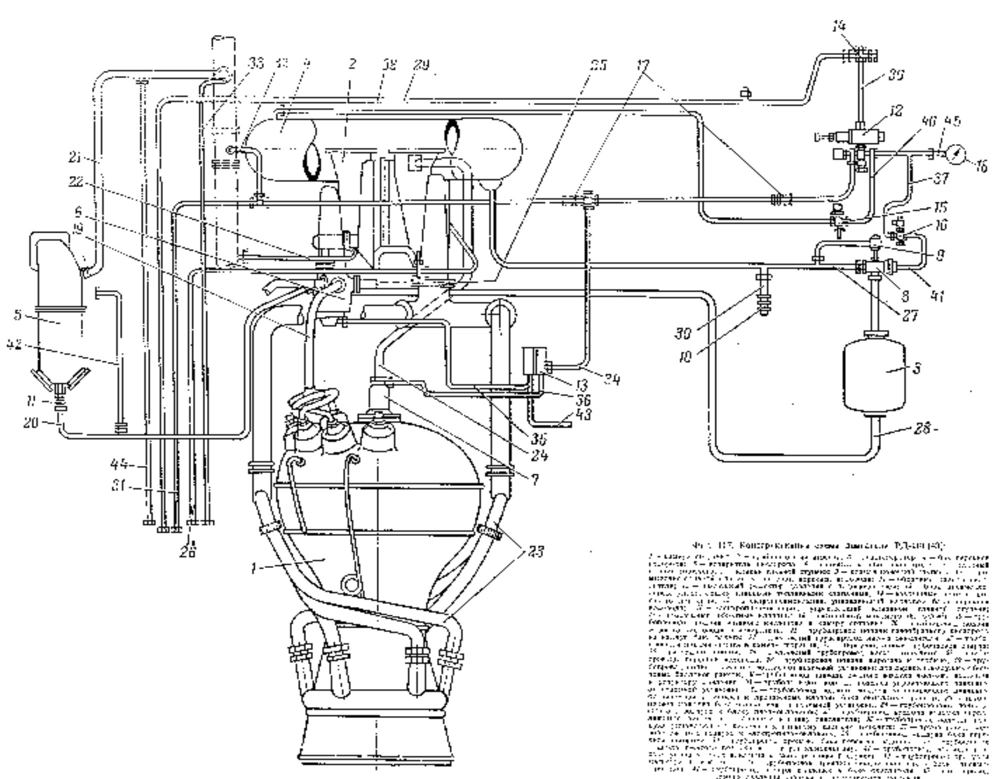


Fig. 11 The plumbing connection diagram of the RD-101 with its toroidal tank.

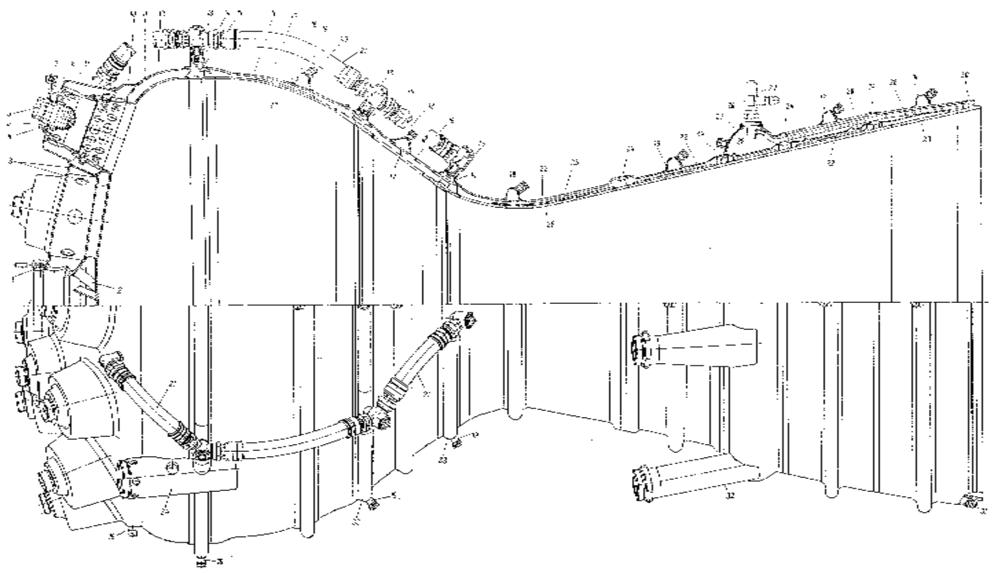


Fig. 12 The notably lengthened combustion chamber of the RD-103 was both the high point and the end point of the development of alcohol-fuelled rocket engines in the USSR.

Fig. 13 Stuck in a corner in shame: The RD-103 in Korolev's training room at RKK Energia in Moscow. To the left, an RD-108.

ics Institute had conducted an extensive test series of models of ribbed cooling walls for combustion chamber regenerative cooling. Baum's team decided that the inner blanket, which should consist of many parallel slots in the long axis of the motor with various dimensions, had to be hermetically bonded to the outer blanket. The method of bonding was the problem. Three general solutions were found:

A) Inner blanket of steel, milled channels consistent with the lowest possible wall strength, filled with wax, coppered, galvanised with a nickel intermediate layer, covered by a steel wire band;

B) Inner and outer walls of steel, channels milled, coppered, both walls hard-soldered;

C) As B, but with the bars scored on the inner wall.

Glushko's engineers wanted an inexpensive mass production - so they took as their basic assumption the first solution with inserts of steel for both walls.

There were also those with more exotic ideas in the Khimki collective. The most important property for the inner wall was the fast conduction of heat from the hot side of the wall to the cooling medium. Coppersmith Erich Drews argued for use of the best possible material: copper, with a melting point of 1083° C, had the best heat conductivity (after silver). The welding engineers Hugo Broetler and Walter Schierhorn pointed out pure copper's poor heat strength and noted that the electrodes of their resistance welding machines, made of silver-bronze, were better. For mass production of expendable rocket engines silver was too expensive - a chrome-copper alloy would have similar material properties. A test run was made of walls of milled copper with soldered-on steel plates. These were water cooled and heated precisely with cutting torches. The results were assembled and passed to the Russians.

New propellant mixing nozzles could also be based on previous work. A German report from the time of their post-war Soviet employment in Germany was known from the digest of results from the rocket sector. Werner Baum had already composed a report on mixing injectors of various layouts, of which the guide nozzles had provided the best mixing of propellant in the liquid phase. His works were the 'Bible', the standard reference work for the Russians in the injection sector of the rocket engine.

This one source assembled the experience, mistakes, patents, and critical results of combustion chamber development at Kummersdorf, Peenemuende, and Dresden. He was also aware of the letters of engineer Lindenberg of the Technical University of Dresden to Peenemuende's Director of Engines, Dr Thiel [20]. These provided withering critiques of the leader of the Dresden and Berlin Ignition and Combustion working group, Professor Beck (who was killed in a car crash against a linden tree immediately thereafter). Here, in the notes from August 9, 1943, was the fundamental result which the Khimki Germans discovered and used. These would lead to the first successes in Soviet space travel: "... a good arrangement of propellants can with secondary mixing dispense with expansion and turbulence in a wider combustion space..." This meant no 'basket head' chamber, but an especially simple, direct, cylindrical wall. The full development of this idea came only after many test series. These results were embodied in a patent of September 16, 1943, classified for military reasons as a 'Combustion Chamber for Jet Engines' [21]. The patent named Dr Zinner of the Technical University Dresden, Dr Thiel of Karlshagen, Dr Kuettner of the Technical University Dresden, and others. In the archives of the "Deutsches Museum" (German Museum) Munich, are further results of the inventors, most important of whom was Dr Mertz, Head Engineer of the Machinery Laboratory of the Technical University Dresden, the original inventor of the specially arranged nozzle. The most important new point was the concentric nozzles, through which the propellants were guided and mixed in the nozzle in the liquid phase. This allowed the barrel-shaped chamber to be abandoned.

Baum's group proposed various new guide nozzles. The recommended form was very similar to the Mertz nozzle. Further the nozzles should be arranged in a honeycomb pattern on the mixing plate with a ring of fuel guiding nozzles on the periphery for film cooling of the combustion chamber walls.

Together with the recommended engine design the Germans noted the following development plan:

- Test chamber with a single nozzle to optimise the thermo-fluid dynamic processes of the single guiding nozzle solution;
- A 4 tonne thrust combustion chamber with the old bored mixing plate to test the new walls of copper alloy within and the new high alloy steel without;
- A 7 tonne and a 25 tonne thrust combustion chamber to test the various mixing nozzle plates with the new walls;
- A 120 tonne test article.

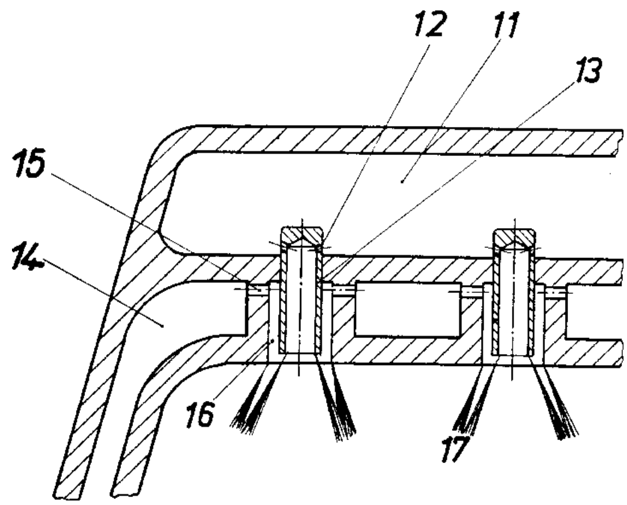


Fig. 14 The decisive excerpt of the patent "Combustion Chamber for Jet Engines" by Dr Mertz and others. Note especially the ordering of the 13 and 16 guide nozzles one to the another. Through drilled hole 15 fuel flowed out of area 14 and through drilled hole 12 oxygen from area 11.
(© German Museum/Munich)

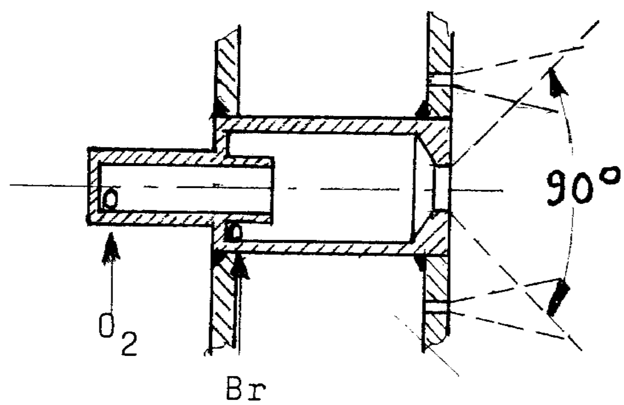


Fig. 15 The recommendations of the Germans at Khimki for the Soviet engines, as Werner Baum had already sketched at Nordhausen in 1947: the oxygen guide nozzles were shortened, so that the fuel mixed while still in the liquid phase.

The Germans came no farther than this. The plans for the 250 tonne thrust engine were left behind from the start. In September 1950 the rocket engine experts were allowed to return to Germany. But before this they had conducted research on a cobbled-together test stand of A4 parts, called 'Liliput'.

Work began in 1948 to test the guide nozzles of new design and a test series of various propellant combinations. This was especially desired in order to introduce aircraft-grade kerosene as a rocket fuel. Up to 100 kg thrust was obtained from the KS-50 (= nominal 50 kg thrust), as the Russians prosaically designated the engine [22 and 23]. The main problem was optimisation of the dual propellant injector nozzle. The cavitation of the oxygen in the upper nozzle section made reproducibility of the propellant drop size and dispersion difficult. Over time empirical formulae were derived for calculating the geometric structure of the nozzles that would

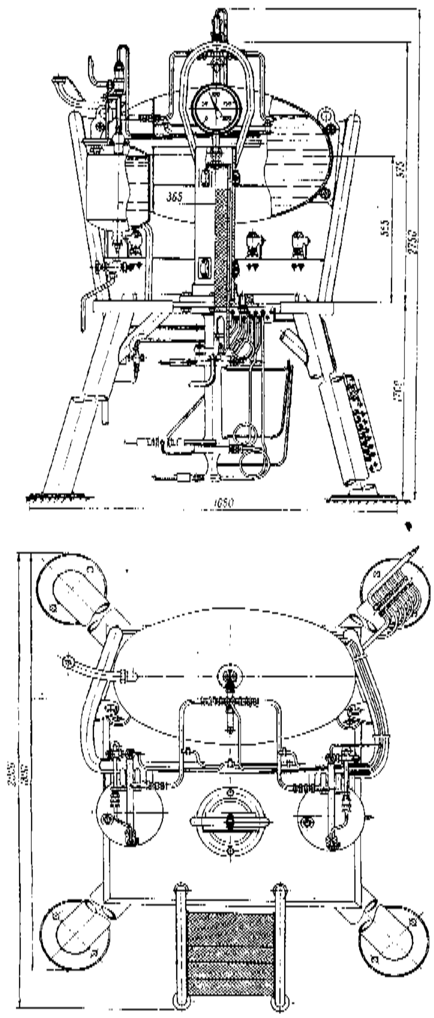


Fig. 16 Experimental test stand KS-50. The water-cooled combustion chamber for a guide nozzle lies between the pipe framework of the lower part.

provide the greatest throughput. The concentrically-spraying hollow cones led to outstanding fully conical atomisation. The characteristic chamber length of the combustion chamber could be substantially reduced. The specific impulse increased.

Liliput was originally of a copper layout, with the inner chamber wall coppered, with soldered-on ribs, upon which profile steel construction elements were soldered at the high points. The engine was water cooled.

Both Germans and Russians agreed that with higher propellant flow and to withstand the combustion products, the chamber had to be made of thin walls of highly conductive copper layers, laid out a few millimetres apart. This led to the supporting steel envelope, which served not only as protection but also provided a heat sink at minimal mass.

In the unique fabrication drawings of the Liliput chamber the primary elements of the German ideas for future combustion chambers were first realised.

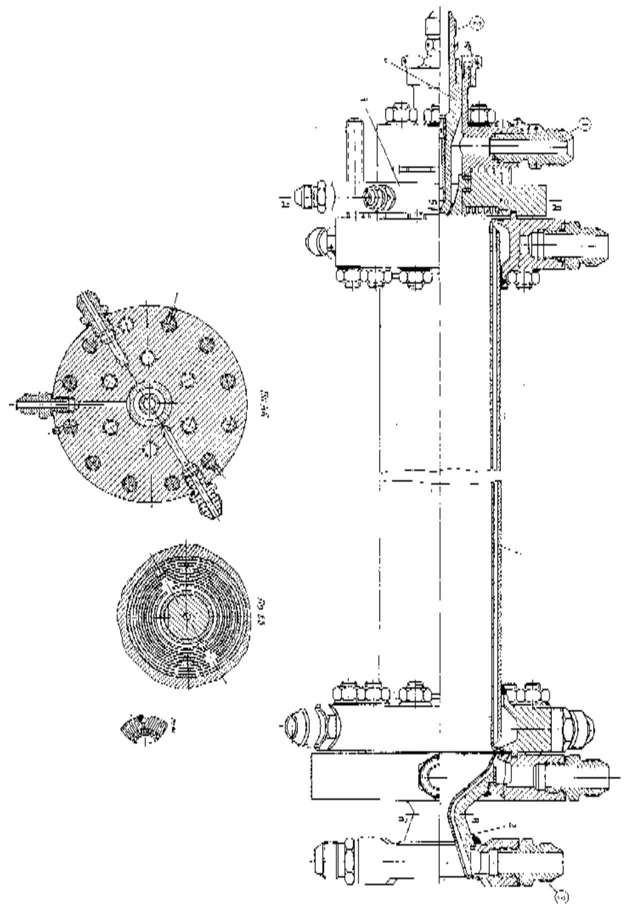


Fig. 17 Cutaway combustion chamber of the "Liliput".

These included the milled vertical slots in the exterior of the inner combustion wall, arranged along the wall in varying quantity and size; the soldered-on copper bars on the outer steel wall; and the welding of the cupro-steel ring elements, one under the other.

But this was the last time that the Germans worked closely on realising actual hardware. The Germans were not invited to participate further in the research. Somewhat later Baum received a special invitation to review research on the 7 tonne engine. He observed: " The vibration response was good, but the pictures of the exhaust indicted a high level of oxygen overshoot, resulting in rapid burn-through. It had happened to us as well."

4. The RD-110: A "Monster" that was Never Tested

The Russian designers sketched out designs for a new rocket series as early as 1947. Korolev's R-3 design adhered faithfully to tradition with a conventional layout. It had a cylindrical body 27 m long, 2.8 m in the diameter, with a cruciform tail - to a certain extent a scaled-up A4 [24]. Its 71 tonne lift-off weight required an enormous new engine, the RD-110. In the final configuration the R-3 looked somewhat less

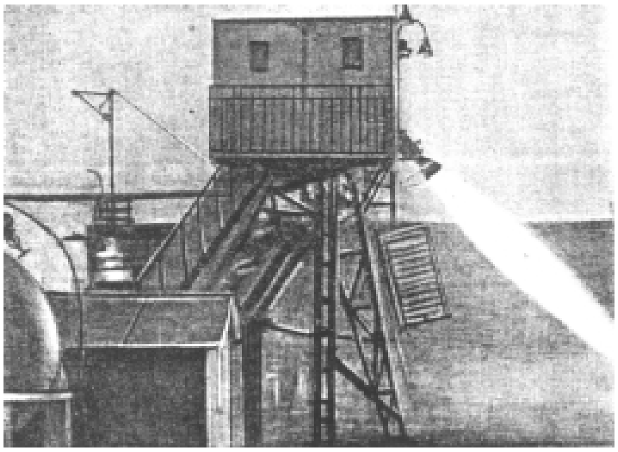


Fig. 18 An unusual photo from Khimki: a test run of the 7 tonne thrust combustion chamber in a test of injector plates.

conservative - the enormous fins, which represented only dead mass, were deleted [25]. At the time of Korolev's defence of the project on 7 December 1949 his critics believed that a rocket without these stabilisers would be statically unstable, and would require massive jet fins [26]. But would it have really ever flown?

Specifications for a rocket motor of over 100 t thrust had already been issued. The RD-110 was to produce 120/140 t thrust (sea level/vacuum; 1176/1372 kN) at a 60 kp/cm² chamber pressure using kerosene fuel to obtain an effective sea-level exhaust velocity of 2390 m/s. The first rough German calculations for this combustion chamber resulted in impressive dimensions: combustion chamber diameter 1500 mm; about 3500 mm in length with an advanced parabolic-shaped expansion nozzle. The complete engine assembly had a maximum diameter of 1800 mm, was 5200 mm long, and weighed 2.1 t wet [27 and 28]! In its external outline the chamber resembled the conventional alcohol engines. In place of the model 39's preburner cups, 18 flat injector disks would be integrated. The design of these would have been tested earlier in small test combustion chambers. Before they could go into the detailed design, much hard development work was required. How should the chamber wall be structured? How would the propellant injectors look? To solve these problems the Liliput research engine was used to develop the copper network chamber wall and optimise the mixing nozzle.

Glushko's team now drew from the accumulated mountain of know-how obtained from the Germans. The German's suggested 7 tonne thrust test engine for the mixing injector plate of the RD-110 was promoted to the "Russian" experimental combustion chamber ED-140. The structure of the wall, the ex-

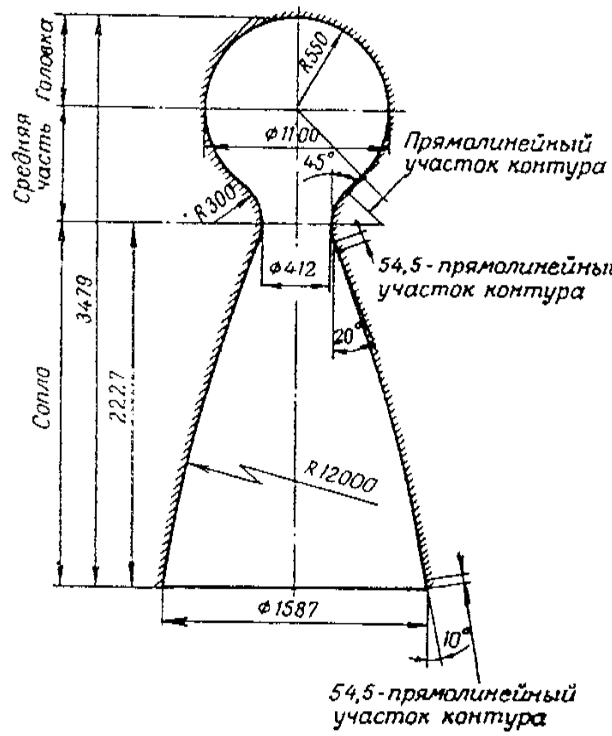


Fig. 19 The gas dynamics profile of the 120 t thrust RD-110 engine.

ecution of the flexible mixing head layout, and particularly the type of the mixing nozzle was attributable to the work of Werner Baum, his fellow constructor Bernhard Gerhardt and others (Gerhardt was the person, who suggested graphite instead of molybden for the jet vanes of the A3 in Kummersdorf).

During the test phase 1949/50, 194 test runs of the engine were made with 45 different mixing injector plates. This required 20 different modifications of the engine [29]. As a result of this test stand work an injector was identified that allowed consistent running of the ED-140 with a normal start and continuous operation. Larger problems had to be overcome in the design of the combustion wall. The Liliput (KS-50) engine's red copper material had a high heat conductivity, but not the necessary heat resistance. The Germans had suggested use of Kuprodur (a chrome-bronze copper alloy with two per cent chrome content). But at that time the metallurgical industry of the USSR was not able to smelt alloys of the required purity. Contamination by foreign materials made production of this material very difficult. Eventually the Russians succeeded in development of a chrome-bronze alloy with the necessary thermal and physical properties.

In preparation for quantity production of the RD-110 extensive research had to be done into the technology of soldering homogeneous and differing materials. That led to the development of flux-free resistance vacuum soldering for the bronze steel connections using a hard silver-copper solder. After 1950 welding of rustproof highly alloyed steels was accomplished using automatic submerged arc welding. Bronze connections were welded with a high melting-point electrode. The Germans had earlier been required to design their engines using only low carbon heat resistant structural steels (boiler plate). Other new technologies included deep-drawing of individual ingots of bronze and steel and high-speed milling of the channels in the copper alloy wall. With the optimisation of the ED-140 and the mastery of these processes all seemed ready at the beginning of the fifties for the manufacture of a giant engine of 120 t thrust [30].

There were, however, thermal difficulties with the test engine, since the Soviet designers wanted to dispense with "wasteful" film cooling in the mixing head area. The fuel within the conventional cooling circuit began circulating at the nozzle end. By the time it reached the end of the combustion chamber, it was at such a high temperature that sufficient cooling could not be ensured. Therefore the Russians developed a separate cooling circuit for the injectors, which was complicated by the fact that the central fuel main valve was not located directly on the combustion chamber since the Russians had installed 19 injector disks.

They decided to cool the critical sections (nozzle and constriction area) by means of water in an extra cycle, which required additional pumps and heat exchangers. Before beginning component manufacture calculations and analytic measurements indicated that safe burning was possible in the RD-110 using kerosene cooling only. For safety's sake slot film cooling was installed at the transition of the chamber constriction as used in the alcohol engines. The 1951 combustion chambers thus did without the water cooling circuit. They passed hydraulic and supercritical tests easily. These test engines used the injector plates which had passed combustion tests successfully in the ED-140.

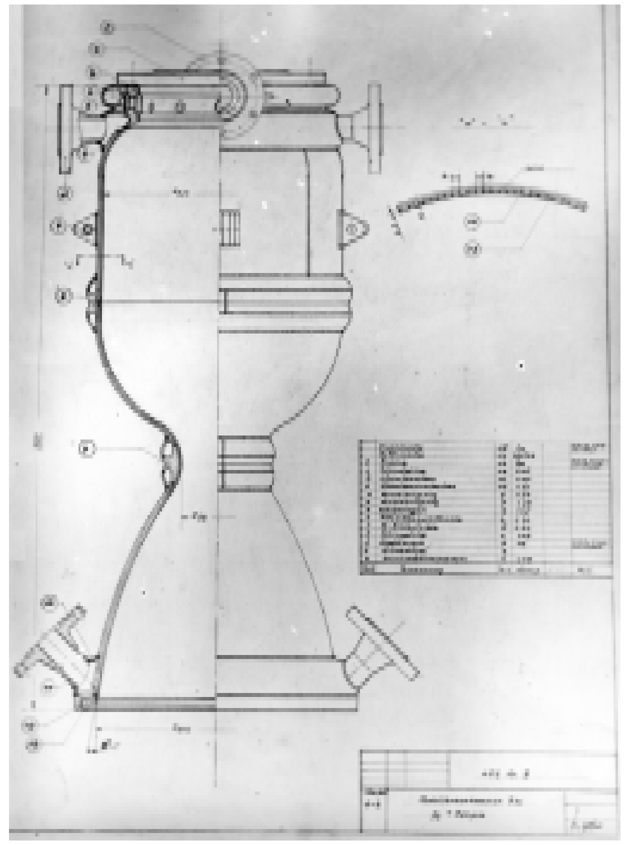


Fig. 20 Combustion chamber No. 3 with 7 tonnes thrust for the development of the mixing injector plates from the German design department.

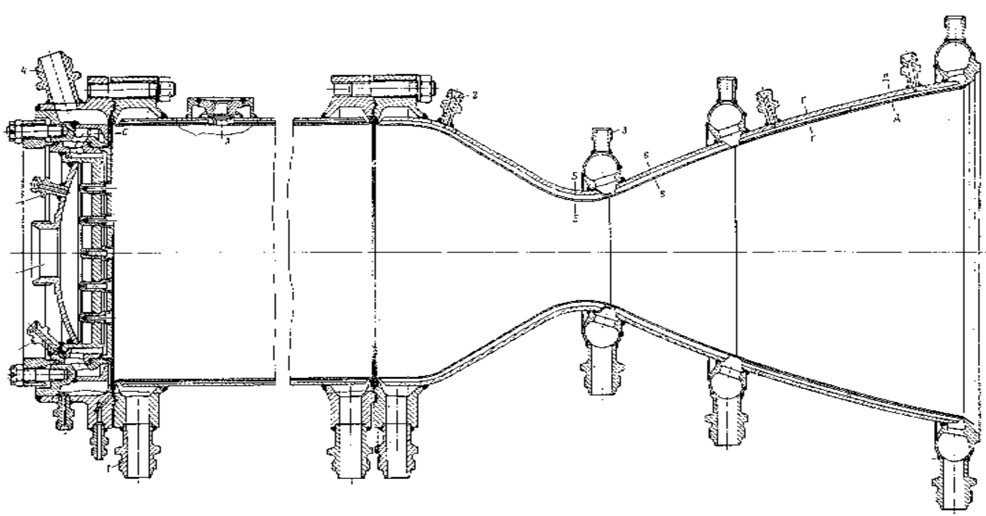
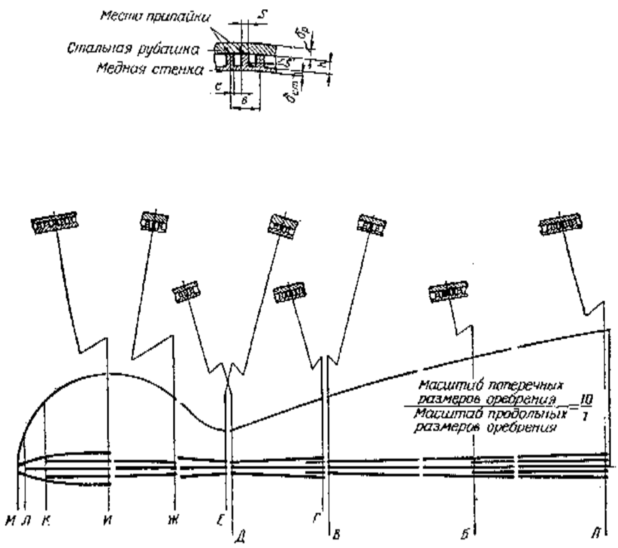


Fig. 21 The German 7-Tonner in its Russian version. Particularly notably are the Mertz nozzles in the Baum variant. These guide nozzles with liquid phase mixture derived their optimised configuration from the test combustion chamber KS-50 " Liliput ". One notes that the diameter of the nozzle mixing space is equal to the effective diameter of the mixture fog. 91 nozzles were built into each injector plate.



Сеч.	А	Б	В	Г	Д
δ_p	3	3	3	3	3
δ	1	1	1	1	1
в	6,25	5	3,04	5,36	2,92
s	1,5	1,5	1,5	1,4	1,4
s'	1,75	0,5	-	0,96	
c	1,5	1,5	1,54	1,5	1,52
h	4	4	4	4	4
n	800	800	800	450	450
n'	800	800	-	450	-

Сеч.	Е	Ж	И	К	Л	М
δ_p	5	5	2,5	2,5	2,5	2,5
δ_{cm}	1	1	1,5	1,5	1,5	1,5
в	2,92	2,81	15,5	11,5	5	3
s	1,4	1,3	1,5	1,5	1,5	1,5
s'	-	-	1,5	[illegible]	0,5	-
c	1,5	1,51	2,125	1,5	1,5	1,5
h	[illegible]	4	3,5	3,5	3,5	3,5
n	450	900	225	225	225	225
n'	-	-	225÷450	225÷450	225	-

Fig. 22 The geometrical dimensions of the milled cooling ducts of the RD-110bronze steel combustion chamber.

Hot firing (ignition with a pyrotechnic mechanism) of the RD-110 never came. Did the Russians have doubts that the cooling was not sufficient, or just decided to move on to a better engine? Werner Baum, on whose No. 4 design the RD-110 was based, noticed critically: “I did not have faith in this implementation and am convinced that it would not have functioned. I could not understand what kind of damping system would control the anticipated combustion oscillations. As early as 1948 Glushko had proposed cooling of the combustion chamber with water and the drive of the turbine with steam. In a discussion with Glushko I was asked to comment on the suggestion of List for a steam distillation unit. I replied negatively.”

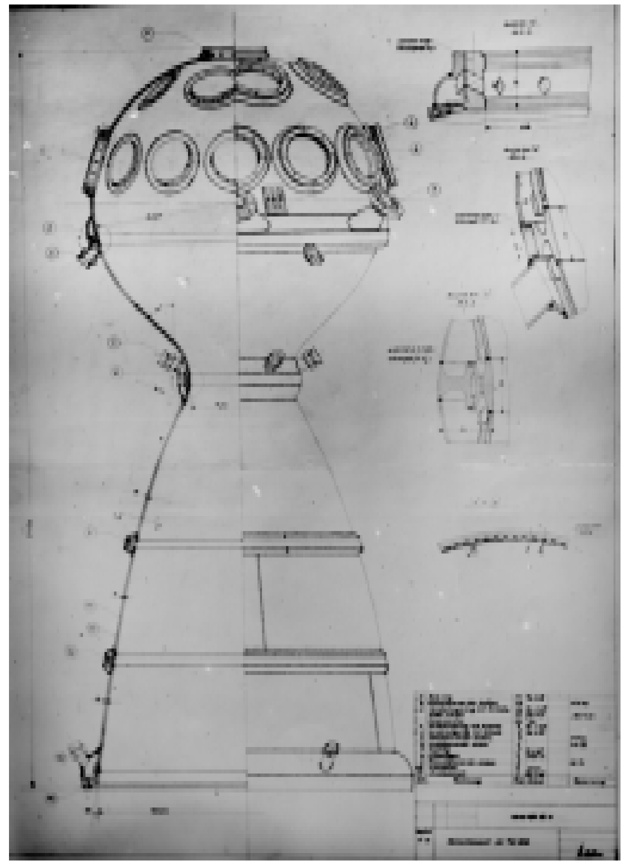


Fig. 23 The German combustion chamber for the project No.4....

The Russian chief designer for small rocket engines, Alexei Mikhailovich Isayev, reached a similarly negative conclusion in regard to the RD-110: “The resulting design was too complicated and unsuitable for series production.” Several designers pointedly favoured the competing engine D2 of A. I. Polyaniy to the R-3. But Korolev, in his defence of the project, noted that for several reasons only Glushko’s engine was considered in the design calculations for the R-3 [31].

Luckily for Glushko the cancellation of work on the

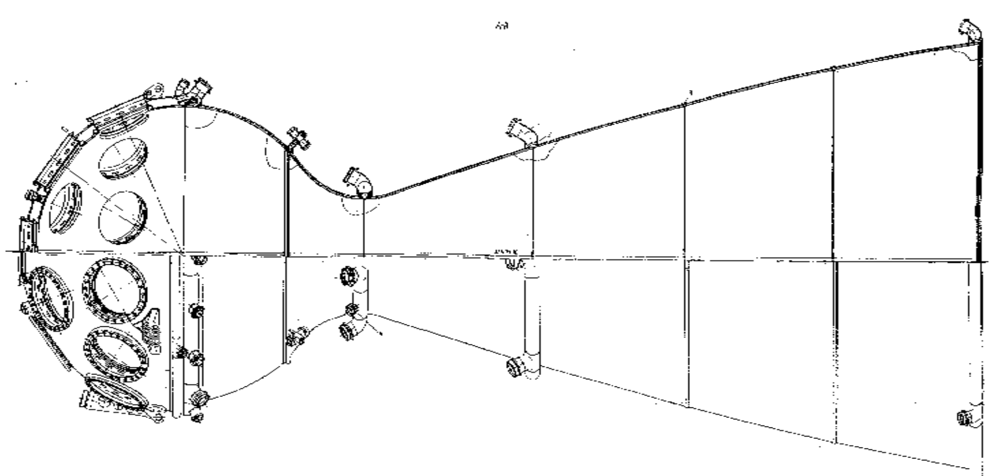


Fig. 24 ... and their Russian counterpart. Apart from the basic similarities, a smaller combustion chamber and a slimmer nozzle are noticeable.

R-3 in 1951 also killed the RD-110. Otherwise it would have become extremely difficult to deny the heavy involvement of the Germans in Russian engine development. Eventual public revelation of the R-3 would have shown sensationally accurate agreement of the Russian design with that of the German team.

5. The Most Secret Engines

On 9 April 1949 Soviet Arms Minister Ustinov went to Groettrup's German "rocket collective" on Gorodomlya Island to request design of a rocket that could deliver a 3 tonne nuclear warhead over a 3000 km range [32 and 33]. Konrad Toebe, one of the designers on Gorodomlya, headed a working group that designed a variety of technical approaches to the problem [34]. In reviewing these variants one notices two-stage rockets like the R-12a/R-12b, which fill gaps in the series of known Soviet rockets and engine designations. Note Korolev's remarks at the plenary session of the NII-88 scientific-technical committee that reviewed the draft project of the R-3 on 7 December 1949: "...for the further rational development of rockets of large range it is meaningful and necessary to develop in the near future a single-stage ballistic rocket of long range which exhausts completely the possibilities of non-staged rockets. That is important, since if one possesses a rocket of simple design with large range, then this rocket could be used as part of more complex staged rockets..." Korolev presented three fundamental layouts of staging (aside from two designs using winged bodies):

Layout No. 1: Jettisonable tanks;

Layout No. 2: Vertically-stacked single-stage rockets;

Layout No. 3: Parallel-connected single-stage rockets (the so-called packet rocket).

In addition, Korolev recommended: "...in the case of longer ranges (over 3,000 km) the staged rocket according to Layout No. 2 is the most efficient from the point of view of the lowest take-off weight. The most inefficient is the parallel staged rocket according to Layout No. 3. However Layout No. 3, in our opinion, is nevertheless the most realistic layout for the achievement of very long ranges" [35]. That position is attributable to the low reliability of the alcohol series engines at that time. How could the reliable ignition of upper stages be guaranteed, when the RD-101engine of the R-2 was achieving a reliability of only 86 % [36]?

At the same time that the R-3 project was underway, staged rocket designs were on the drawing boards. These included designs based on the winged German "America Rocket " A9/A10, and more modern technology as represented by the R-12a/R-12b (official designation; known by the Germans as the G-2 and with the secret Russian designation R-6). This was followed by development of the R-14 (German G-4 or secret Russian R-10), which was the Germans competitor to the R-3. The R-14's conical shape was better suited for both single stage and packet rocket applications than the R-3.

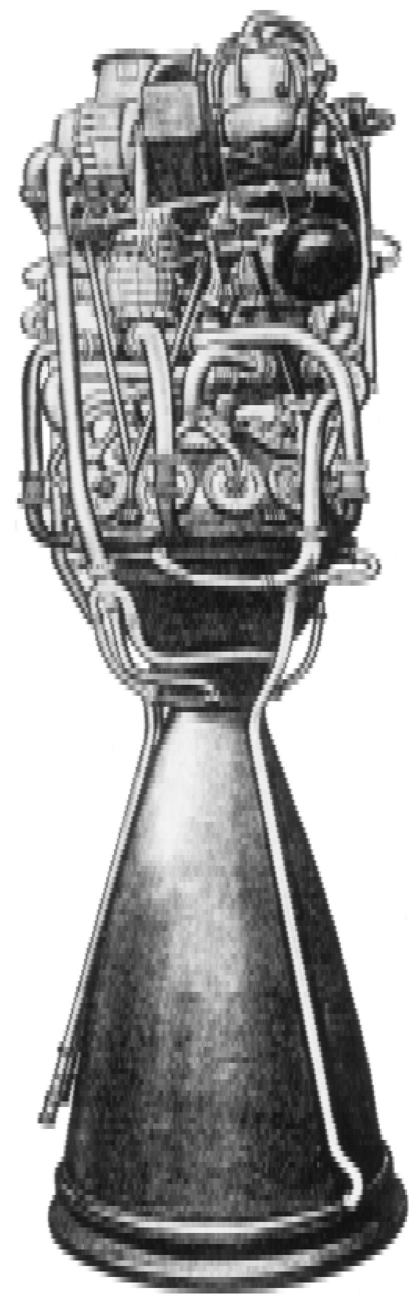


Fig. 25 A fully assembled RD-110 in the kerosene cooled version.

An upper stage engine had to be developed for use in these sequentially-staged designs. The Gorodomlya team had already supplied the complete design for such an upper stage in the form of

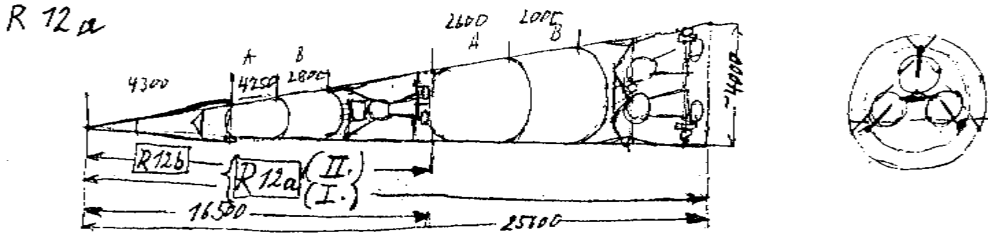


Fig. 26 The R-12 from the German Groettrup team represented a technological building block toward rocket staging and engine clustering.

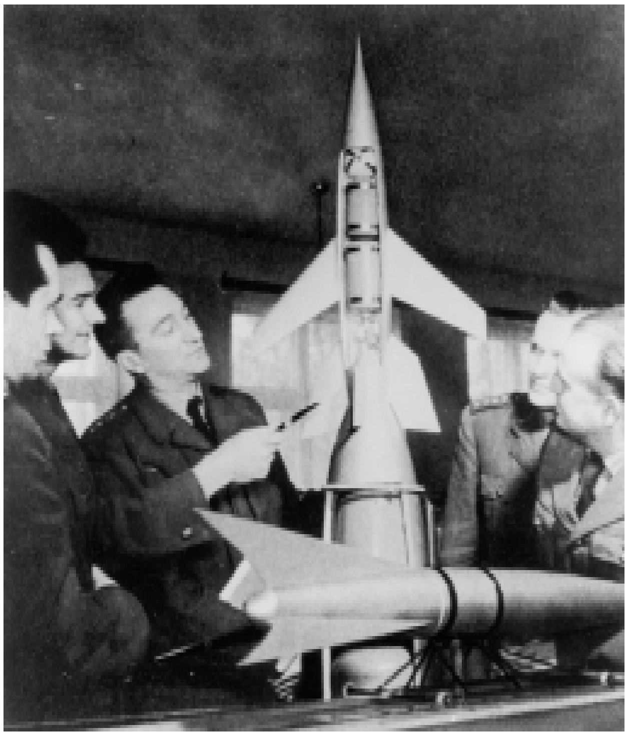


Fig. 27 Officers of the Warsaw Pact familiarise themselves with models of long range rockets. The model the German A9/A10 is easily recognisable.

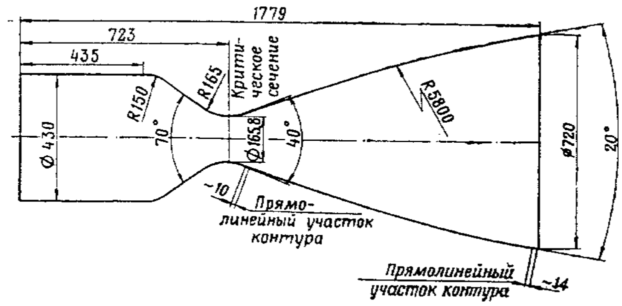


Fig. 28 The geometrical profile of the 25 t-nozzle.

the super-light R-10 rocket (German G-1 or secret Russian R-4). This had an empty weight of 1870 kg with an engine of 25 t thrust [34]!

The Korean War at the Soviet's back porch apparently resulted in the decision to cancel the R-3 and leap-frog to ICBM designs (maybe stacked secret R-4/ R-6). Werner Baum and his colleagues were pressed to finish their work as quickly as possible. The drawings for the new design 25-tonne thrust engine were issued on a crash basis from the middle of 1950. Werner Baum remembers very well his last combustion chamber design at Khimki: "...for the 25 tonne experimental chamber a combustion chamber pressure of 60 atmospheres was planned. The propellants oxygen/kerosene, at a mixing ratio of 2.24, would be injected into the chamber through 300 tangential guide nozzles. 60 nozzles in the outermost ring were devoted to film cooling of the chamber walls. " The 25 tonne design represented a straightforward linear scale-up of their 7 tonne test combustion chamber (the "Russian" ED-140). Fitted with a bell-shaped expansion nozzle, this resulted in a lightweight combustion chamber of approximately 200 kg mass. In contrast to the RD-110 the Germans used milled channels only in the areas of narrowest cross-section. Otherwise the flow rate in the cooling channels could not meet the heat absorption requirements, as indicated by technical difficulties in large engines such as the RD-110. The German designers suggested curved copper sheets, which could be adapted easily to the required contours and be hard soldered to the interior and outer walls for the nearly conical sections. This approach was ideal for mass production.

The fate of the Germans' last "child" (RD-102?) remains unknown. Did it serve as a subscale test bed for the 120 tonne or 250 tonne engines? Or was it built and made flightworthy? They never knew. Werner Baum is today convinced that the "...new 25 t-combustion chamber got as far as construction of the firmly connected chamber walls and proof-test of the fuel cooling. I also was asked to work on a new high expansion ratio nozzle...." which points to an upper stage engine!

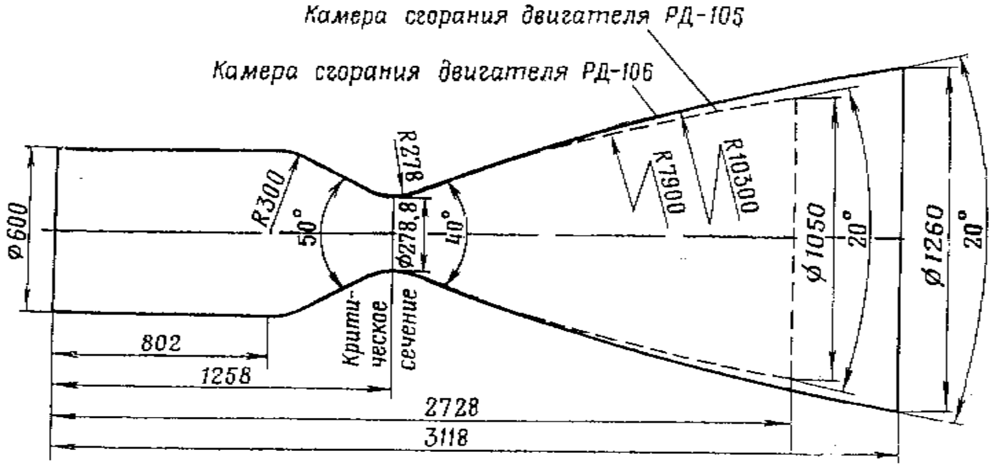
After the German specialists were allowed to return to their homeland, they awaited public evidence of the rocket development they knew to be underway. But there was no sign of this in 1950. For the time being it remained invisible. The Baum group had trained the experts around Glushko well. The next engine which would have been developed (RD-104?) would have followed the German's recommended model: ED-140 x 18 = RD-110. A 250-tonne engine would have been composed of ten to eleven 25-tonne injector plates combined in a single combustion chamber. This would have been a simple method, using the wealth of experience of the Germans and the RD-110, to power Korolev's intercontinental sequentially-staged rocket. Thus would two birds be killed with one stone: the 25 tonne injector as the basis for both the 250-tonne thrust first stage engine and the 25 tonne thrust second stage. The first tests indicated the good throwing arm of the Germans. Or so at least it probably seemed.

6. Short Intermezzo: The RD-105/106 Series

Suddenly, surprisingly, 1951 brought the cancellation of the R-3, the technology testbed R-3A, and the derived sequentially-staged versions. The Soviet military doctrine required genuine intercontinental range rockets. This was the baptism of the packet-scheme R-7. The 170 tonne rocket was required to propel the 3-tonne nuclear warhead of Andrei Dimitreyevich Sakharov's collective up to 8000 km. As intermediate range back-ups it was decided to use modifications of available rocket designs from Korolev's NII-88. These projects became the acid test of two future chief designers. The R-5 - the first strategic medium-range missile - was developed from the R-2 under the leadership of Mikhail Kusmich Yangel. Vassili Pavlovich Mishin was responsible for the parallel project. He developed the so-called tactical-operational rocket R-11 from the R-101 - itself the Russian version of the German Wasserfall air defence rocket [24, 37 to 39]. In the case of possible difficulties in development of the R-7, a fall-back design was available: the R-55 rocket, consisting of an R-11 (then R-17) as second stage to an R-5 [40 and 41]!

The R-7 Semyorka ("good old number seven") was fundamentally based on the design documents of the Groettrup team. The Russians could not deny that the conical form of the German G-4 was ideal from the point of view of controllability and static and dynamic stability. Korolev's concept was to combine several small conical rockets á la G-4 or R-3A around a larger central stage. In this way the entire rocket could be ignited at launch. The second stage, with more propellant, would continue operating after the fuel in the lateral blocks had been consumed and they were jettisoned. The maximum dimensions of the blocks was set by the limitations of transport via railway. This final elegant solution shows the results brought about by systematic study of all possible alternatives.

In the years 1951 to 1954 dozens of preliminary projects were completed on the structure, propulsion, controls, and subsystems of the future rocket. Glushko's designs included the RD-105 single-chamber engine for the first or booster stages. This had a thrust of 55 t (vacuum thrust 64 t, dry weight 782 kg). The second core stage would be powered by the flight altitude adapted RD-106 with 53 t thrust (vacuum thrust 65.8 t, dry weight 802 kg). It was expected that their development could be brought to the point of operational readiness in a few years [42]. The good experiences with the linear enlargement of the ED-140 to the RD-102(?) indicated that similar success could be achieved with use of multiple 25-tonne injectors; but then the limits to the approach were shown. A number of serious problems occurred. The most difficult was elimination of high frequency oscillations in the combustion chamber, which were observed as the engine went into the main thrust level regime and continued up to destruction of the engine. It was concluded that complete burning of the propellants was not taking place in the combustion chamber. In an attempt to solve this, the combustion chamber length was in-



Фиг. 9. Геометрический контур камер сгорания

Fig. 29 The geometrical profile of the RD-106/106-nozzles. 817 injectors are in the injector plate!

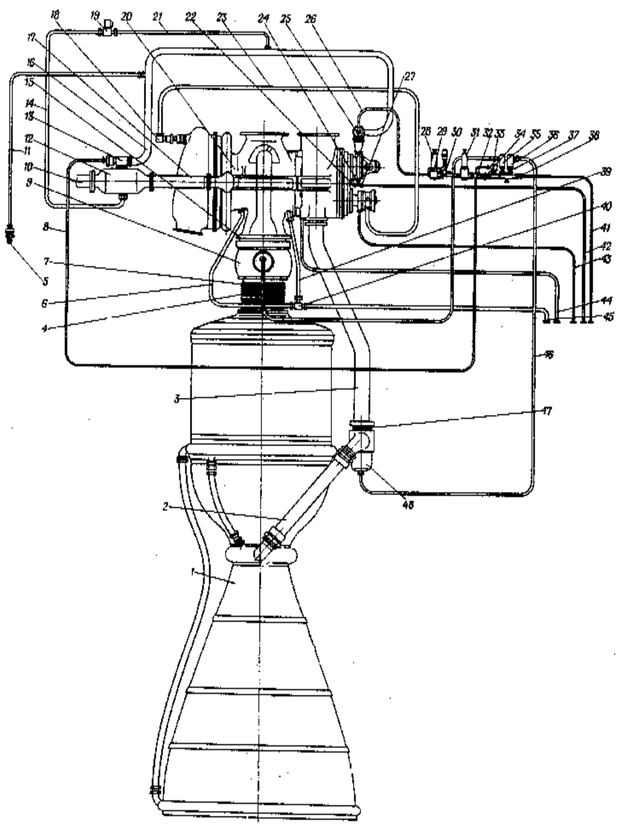


Fig. 30 The plumbing connection diagram of the RD-106. Recognisable proven items from the German Aggregat 4 (five-branch pipe coupling and gas generator) can be noted.

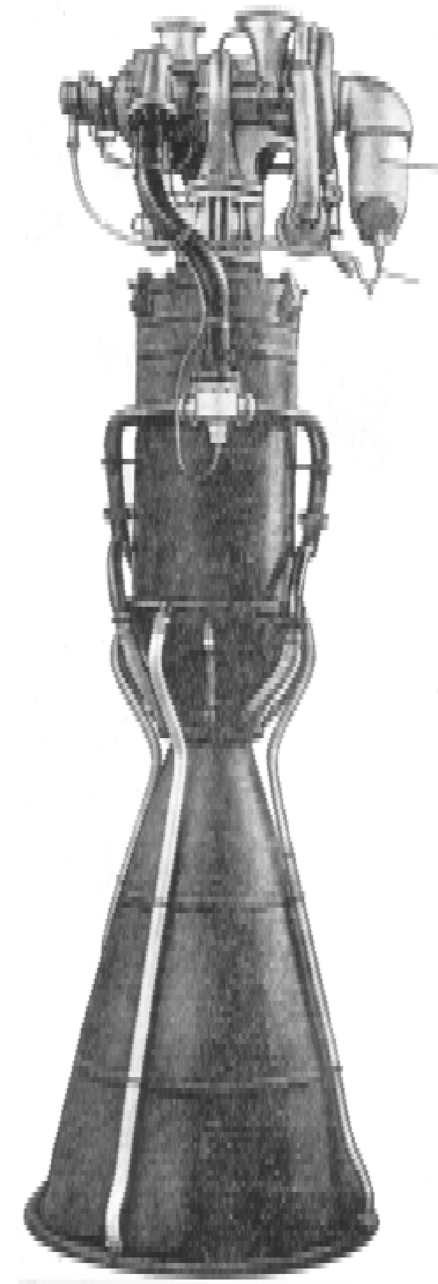


Fig. 31 The RD-105 in its production variant. Combustion oscillations forced the very long chamber design.

creased to unsightly proportions [43]. Meanwhile it became clear that the planned A4-type graphite thrust vectoring vanes could not withstand the calculated 250 second burn time. Glushko, busy with the serious problems with the RD-105/106, had no capacity for the development of small steering rockets to replace the vanes. Therefore Korolev directed his own staff, under the leadership of Mikhail Vassilyevich Melnikov, to develop steering rockets of approximately 3 t thrust based on the German layout [44].

7. From the German Upper Stage Engine to the Most Successful "Russian" Rocket Propulsion

On 20 May 1954 a hard blow disrupted the development of the R-7. The decision was made to change the warhead to a thermonuclear device with the mass increased to 5 t. This required a take-off weight increase of almost 100 t and higher-thrust engines. The RD-105/106 were suddenly without a rocket and were cancelled. As far as the overall rocket was concerned, it was relatively simple to stretch the conical R-7, with the beneficial result of an increased diameter at the base of the individual stages.

At the time of beginning work on the RD-105/106, Glushko also began development of equally powerful engines of the 200 series, which operated with nitric acid oxidisers [45]. Since use of nitric acid was considered a difficult task, it was logical to simplify development of the combustion chamber by reducing the dimensions. The design of the Toebe group for the R-12 (G-2) used several chambers in an engine cluster fed from a single turbopump. A similar design to that of the Baum combustion chambers was the backbone of the Russian R-12 strategic rocket. It was shown that the multi-chamber layout represented a promising solution, also allowing higher quantity production and reduced cost of the combustion chambers. Therefore the obvious near-term solution was to use the clustered chamber concept for the new R-7-engines as well.

TABLE 4:. *Performance data of the Engines.*

Type	RD-110	RD-105//106	German 25 tonne
Fuel consumption (kg/s)	131.3	55	20.8
Oxygen consumption (kg/s)	347.9	149	52.2
Oxidiser to Fuel Ratio	2.65	2.7	2.51
Specific impulse/sea level (s)	244	260//250	263
Specific impulse/vacuum (s)	285	302//310	320
Thrust sea level/vacuum (t)	120/140	55/64//53/66	23

The German-derived test engine for a possible upper stage was taken from storage. In 1954 this had already produced 25 t thrust without large problems. It could be taken as the basis for further advances. The smooth profile chamber would have to be stretched somewhat in comparison to the Baum team's design to increase the characteristic combustion chamber length. However the fundamental technological structure was adequate, consuming in one second 52 kg oxygen and 21 kg kerosene. The kerosene, after it cooled the chamber walls (reaching a maximum 380° C), had an average temperature of 210° C when injected by the 337 nozzles of the injector plate into the combustion chamber. On the outermost of the 10 concentric nozzle rings were 60 kerosene guide nozzles for the wall film cooling. The remaining nozzles used the well-known mixing nozzles of Baum's design. At the narrowest combustion chamber cross-section the cooling circuit was appropriate for a maximum kerosene flow speed of up to 20m/s [46].

Successively two and four-chamber versions were tested. Thermal and sonic reflection waves affected the function of the engine's equipment, which had to be protected by special shields. Melnikov's gimballed steering engines had to be integrated. The complex five-way synchronous operation of all of the engines in the booster rocket was a significant accomplishment in 1956. These entered history as the four-chamber engines RD-107 (first stage lateral blocks, 1155 kg mass, 82.1 tonnes thrust at sea level) and RD-108 (second core stage, 1250 kg, 81.2 t ground-level thrust).

Why did the USSR wait until 1967, at the Le Bourget Air Show, to exhibit the Vostok R-7 rocket and cutaway models of its engines? Werner Baum could explain it on the spot: "... we could determine by examining the cutaway models of the Vostok engines how all of our suggestions, tests, and so on were adopted..." The engines were regular copies of the Germans' projects; but the Soviets had decided that 20 years after the beginning of the development of the engines the process of forgetting had run its course. Those who had worked on the original engines could fix blame by unmasking the so-called inventors; but those, who could have reacted, did not do so. They had no proof for their position. Only today, by looking into Russian archives, can an exact picture be drawn.

The engine is the heart of each rocket. It beats regularly, allowing the other systems to breathe freely. Early successes of the USSR in space depended crucially on the work of the German engine specialists in the office of Glushko in Khimki. Basic ideas from Dresden were collectively optimised by foreign and knowledgeable Russian specialists. The Russians completed the German preliminary work, resulting in an engine

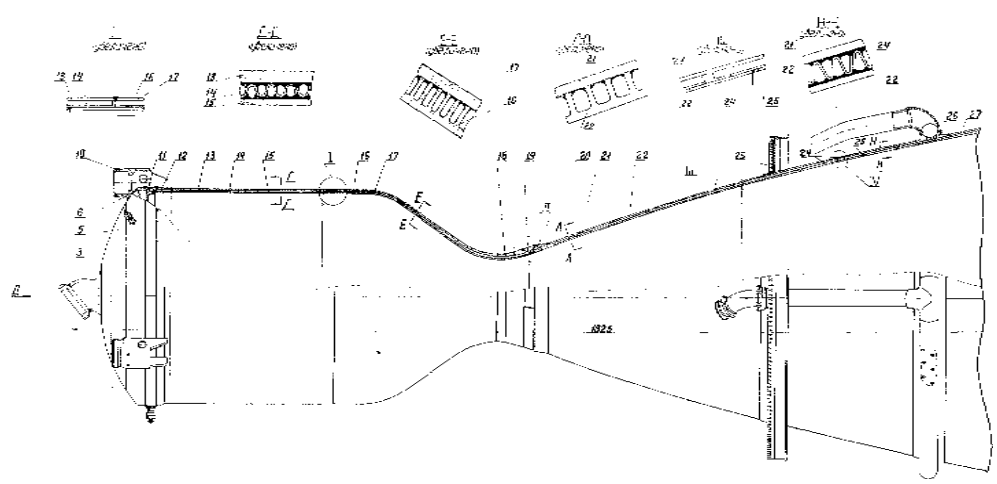


Fig. 32 Structure of the 25 t-combustion chamber: In the upper and lower sections curved copper alloy sheet metals were used. Milled wall elements were employed in both centre sections.

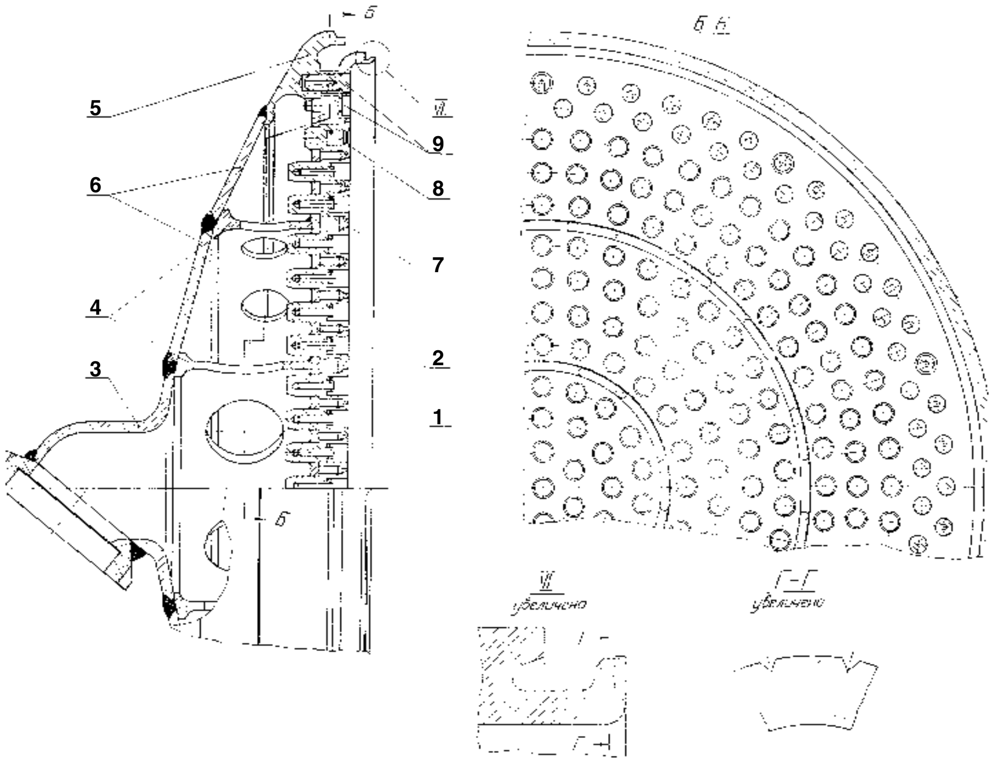


Fig. 33 The mixing injector plate of the 25 t-nozzle shows the arrangement of the liquid phase bipropellant nozzles in concentric rings. Key: 1. base plate (chrome bronze); 2. intermediate base (steel); 3. oxygen flange; 4. annular bars; 5. circular ring section of the combustion chamber head; 6. transition element; 7. bipropellant nozzles (chrome bronze); 8. fuel guide nozzles for film cooling; 9. plugs.

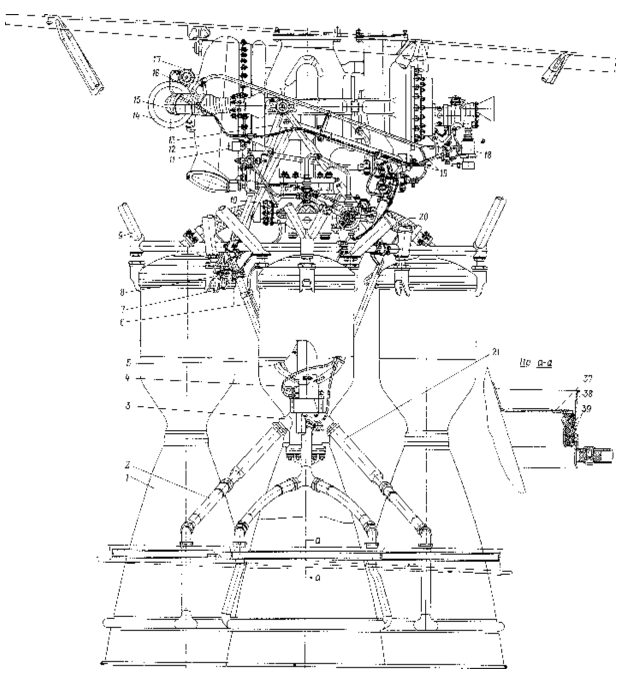


Fig. 34 The RD-107 - four optimised 25-Tonners in a cluster.

family, which had only little similarity with the original A4/V2 technology. Nevertheless the source of this family was the Peenemuende project community.

It is now difficult to deny that the Germans were considerably involved in co-operative design of the rocket motors for the R-3/R-7 and their subsequent

Fig. 35 The RD-107 in a cut.

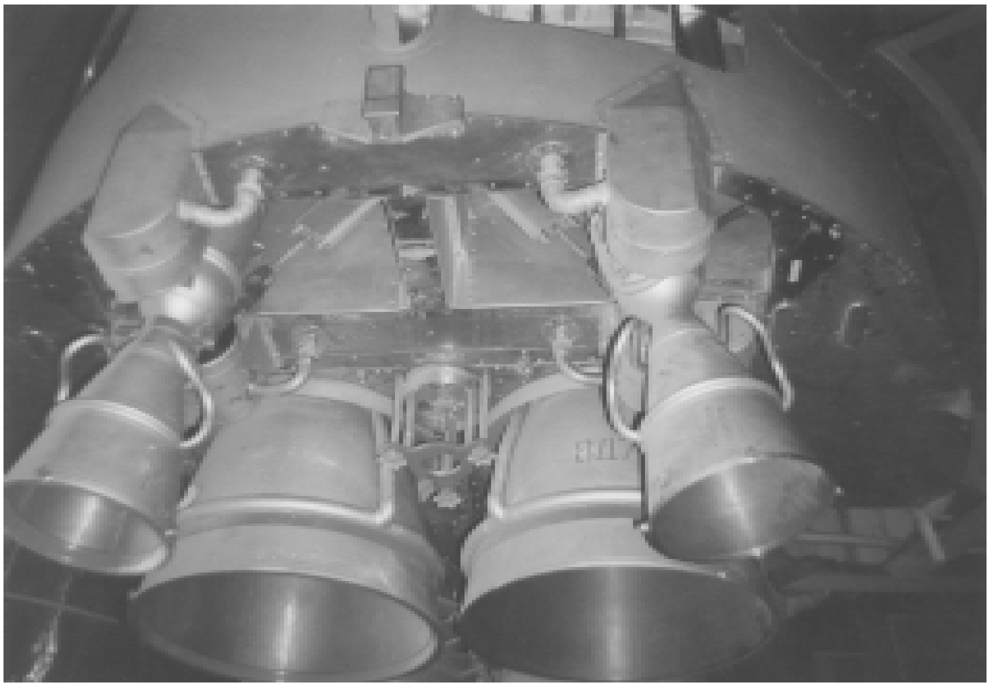


Fig. 36 The RD-107 as built in the first stage of the R-7.

versions; but it will be just as difficult for the interested public to accept this in place of the untruths stated for so many decades.

8. Brief Engine Notes

The family tree of the German/Russian liquid rocket development can be divided into two parts. It can be noted that the engines developed at Peenemuende by the German army were adapted and perfected not only in the USSR, but by other Allied powers as well.

The advancements of the alcohol engines up to the RD-103 were based on the use of the guide nozzle, that was invented intuitively at the end of the thirties by the Dresden Schlick Nozzle Company. The bored hole nozzle did not find its way into operational combustion chambers during the war. The USA, France and partially the Soviet Union developed it later, achieving successful jet atomisation by mutual impingement of the propellant streams. The annular gap nozzle, like the bored hole nozzle an invention of the Technical University Dresden, did not become generally accepted.

Mertz's new bipropellant nozzle, with mixture in the liquid phase, originally designed in Dresden and brought to life by Germans in Khimki, became the basis for all kerosene engines of the Soviet Union. The remarkable designation gap and the large period between the engines RD-110 and RD-105/106 tempted the author to the only speculation in this series of articles: the assumption that the 25 t-

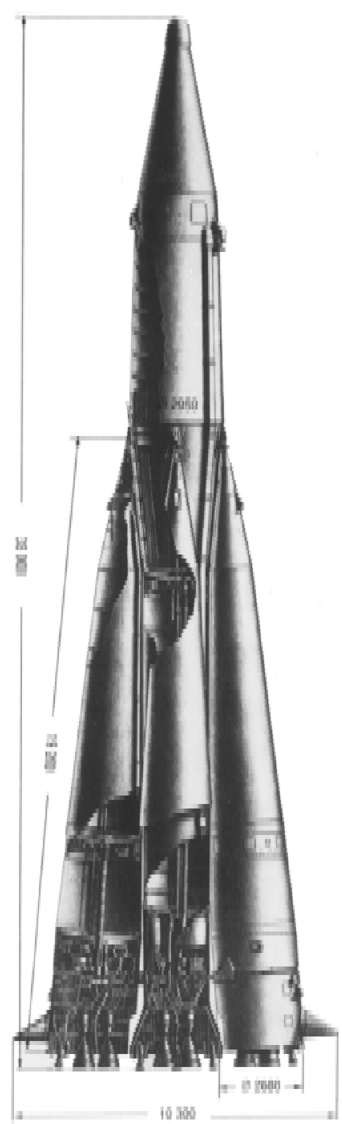


Fig. 37 The R-7 - Basis of all Soviet space flight successes.

engine was designated the RD-102 or RD-104 and was intended for an upper stage. The 250-tonner, the test basis for which goes back to Baum's time in Moscow, also belongs in this category.

9. Acknowledgements

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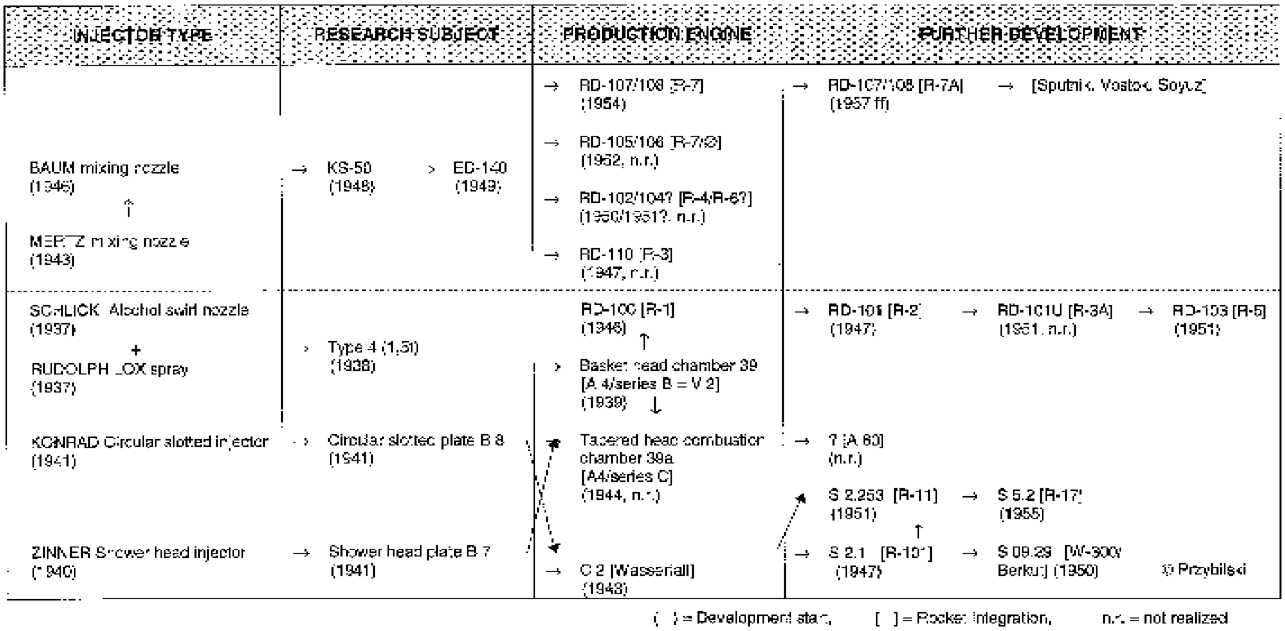

The family tree of the German/Russian liquid rocket engine development

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This article is based on Werner Baum´s arguments to the author (1998 - 2000). A complemented list of acknowledgements followes.

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Updated overview

INJECTOR TYPE	RESEARCH SUBJECT	PRODUCTION ENGINE	FURTHER DEVELOPMENT
		→ RD-107/108 [R-7] (1954)	→ RD-107/108 [R-7A] → [Sputnik, Vostok, Soyuz] (1957 ff)
		→ RD-105/106 [R-7/∅] (1952, n.r.)	
BAUM mixing nozzle (1946) ↑	→ KS-50 → ED-140 (1948) (1949)	→ RD-102/104? [R-4/R-6?] (1950/1951?, n.r.)	
MERTZ mixing nozzle (1943)		→ RD-110 [R-3] (1947, n.r.)	
SCHLICK Alcohol swirl nozzle (1937) + RUDOLPH LOX spray (1937)	→ Type 4 (1,5t) (1938)	RD-100 [R-1] (1946) ↑ → Basket head chamber 39 [A 4/series B = V 2] (1939) ↓	→ RD-101 [R-2] → RD-101U [R-3A] → RD-103 [R-5] (1947) (1951, n.r.) (1951)
KONRAD Circular slotted injector (1941)	→ Circular slotted plate B 8 (1941)	→ Tapered head combustion chamber 39a [A4/series C] (1944, n.r.)	→ ? [A 60] (n.r.) S 2.253 [R-11] → S 5.2 [R-17] (1951) (1955) ↑
ZINNER Shower head injector (1940)	→ Shower head plate B 7 (1941)	→ C 2 [Wasserfall] (1943)	→ S 2.1 [R-101] → S 09.29 [W-300/ (1947) Berkut] (1950) © Przybilski

( ) = Development start, [ ] = Rocket integration, n.r. = not realized

The family tree of the German/Russian liquid rocket engine development