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Chapter 8

HISTORY OF DEVELOPMENT OF FIRST SPACE ROCKET ENGINES IN THE USSR*

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The power base for cosmonautics at the present time is made up of liquid propellant rocket engines (LPRE), whose operating principle was laid down back in 1903 in the classic work of K. E. Tsiolkovsky [1]. Among the complex problems that had to be solved in order to achieve space flight, the paramount one was the problem of developing the chamber for the LPRE unit, which directly creates the thrust (Figure 1). The problem lay in the development of a design that would function reliably under conditions of high mechanical and thermal loads, ensuring at the same time the efficient conversion of the potential chemical energy of liquid rocket fuel into kinetic energy of the jet gas stream. The technical ideas expressed by Tsiolkovsky served as a good foundation for the beginning of the practical work on the solution of the indicated problem.

Tsiolkovsky proposed burning a fuel under a pressure of several thousand atmospheres, and then dispelling the obtained gas in a continuously expanding nozzle that would extend the entire length of the rocket, until the temperature and elasticity values were "completely negligible," right down to the conversion of the combustion products "into liquid and even into ice crystals, which rush out of the tube with startling speed" [2, pp 102, 107]. At the same time, practically all the thermal energy generated during the combustion of the rocket fuel would be converted into the kinetic energy of the jet stream flowing out of the nozzle.

The efficiency of a rocket engine is determined by the amount of thrust obtained from 1 kg of fuel expended in 1 sec. This parameter, called the specific impulse, during the engine's operation under calculated conditions is numerically equal to the jet stream velocity. Together with the thrust, the specific impulse is the paramount parameter of the rocket engine, inasmuch as, according to Tsiolkovsky's well-known formula, it is associated by means of a direct proportional relationship with the velocity attained by the rocket upon the complete expenditure of its fuel.

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The high temperatures, pressures and gas velocities in the chamber determine its high thermal factor. The value of the heat flux density (i.e., the amount of heat crossing a unit of the chamber surface over a unit of time(is nearly constant along the length of the combustion chamber, then increases with a sharply pronounced peak in the nozzle throat, after which it decreases, reaching a minimal value when it exits from the chamber (Figure 1).

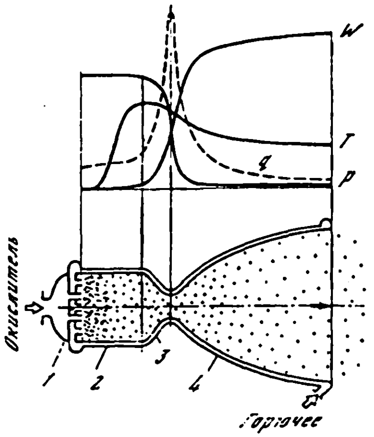

Figure 1 Diagram of chamber of contemporary LPRE and the parameters which characterize its operating process.
(1) the spray injector, (2) the combustion chamber, (3), (4) the subsonic and supersonic sections of the nozzle respectively; (p), (T), (W) the pressure (kg/cm^2), temperature (°K) and the velocity (m/s) of the combustion products, (q) the density of the heat flux (MWt/m^2).

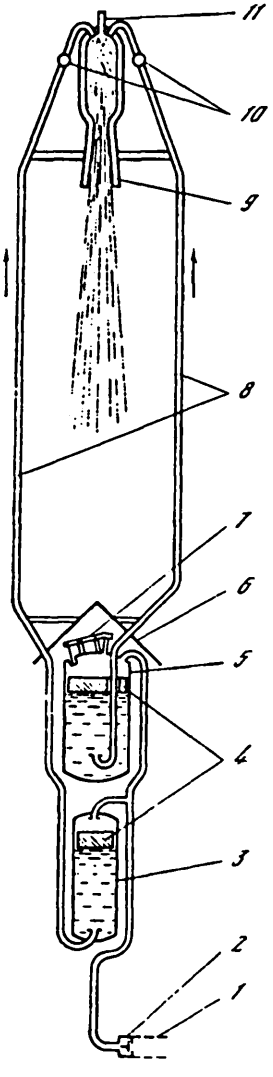

Figure 2 The first liquid propellant rocket, 1926 (launch weight, 4.6 kg).
(1) ground tank hose, (2) check valve, (3) tank with gasoline (benzine), (4) floating stopper valve, (5) tank with liquid oxygen, (6) protective shield, (7) safety valve, (8) feed pipes, (9) chamber with synthetic corundum refractory lining, (10) needle valve, (11) igniter.

In order to keep the chamber structure intact, Tsiolkovsky proposed cooling it with the liquid fuel itself, running the fuel components in the casing along the chamber wall before feeding them into the combustion area [1]. Such a method, called regenerative cooling, is widely used in contemporary LPRE's and is now the most reasonable one. However, its realization was by far not a simple matter. In fact, the introduction of regenerative cooling not only substantially complicated and increased the deadweight of the chamber structure, but also required additional fuel pressure (in order to compensate for hydraulic losses in the cooling system), which complicated the task of developing the feed units.

In addition, in the 1920's and 1930's, when the tests with LPRE's had begun, they did not have sufficiently accurate methods for calculating the heat transfer processes for the LPRE's operating conditions. Therefore, the first experimenters began with the simplest of single-section chambers. And so that these chambers could endure at least several seconds of operation, they were made on a large scale out of heat-conducting metals, immersed in water or in fuel tanks, and placed so that they would be surrounded by the air flow in fuel tanks, and placed so that they would be surrounded by the air flow in flight and so on. R.H. Goddard, who had begun experiments on developing LPRE's earlier than others, was the first to try lining the chamber with refractory material [3, pp 195f]. It was precisely such a chamber that was installed in his first LPR, which was launched on 16 March 1926 (Figure 2).

In order to facilitate the task of developing a workable chamber, many designers went for a reduction in the temperature of the combustion products by overenriching the fuel mixture with fuel oil or ballasted water. Of course, at the same time, the specific impulse of the chamber was also reduced. Goddard, and after him H. Oberth in Germany, proposed cooling the chamber by creating next to the wall a stream of a relatively cold liquefied gas layer [3, p 201; 4, p 470]. To this end, for example, part of the fuel should be fed to the combustion arc along the wall of the chamber. Such a cooling method was called curtain or "internal" in contrast to the "external" regenerative method.

In our country, the practical work in the field of LPRE's and LPR's was begun in 1929 by the Leningrad Gas Dynamics Laboratory (GDL). The group of LPRE specialists, headed by the young scientist and current academician, V.P. Glushko, tested the most diverse chamber designs on stands and, finally, in 1933, developed LPRE's capable of operating continuously over the course of dozens of seconds. In addition, these engines could be used repeatedly. The "Experimental Rocket Motors," the ORM-50 and ORM-52, with which we are concerned, developed thrusts of 150 and 300 kg, respectively. Their chambers had (curtain) and regenerative cooling [5, pp 181, 185]. The curtain was created by the centrifugal fuel injectors located on the steel cylindrical combustion chamber by feeding a small part of the atomized liquids onto the wall. Judging from the fact that the chamber did not burn through for a long time, the curtain, carried along by the gas flow, was retained also in the area of the nozzle. In addition, it was intensively cooled by the stream of oxidizer, which flowed through the conduits formed by spiral ribs on the internal steel wall and covered it with split aluminum bushings (Figure 3). Thanks to the spiral conduits, the velocities and the path of the cooling liquid were increased, the surface area washed by it increased and, as a result, reliable cooling was achieved. Glushko obtained a patent for a chamber with spiral ribbing and split bushings [5, pp 228-230]. This design was widely used in native and foreign LPRE's in the 1930's and 1940's.

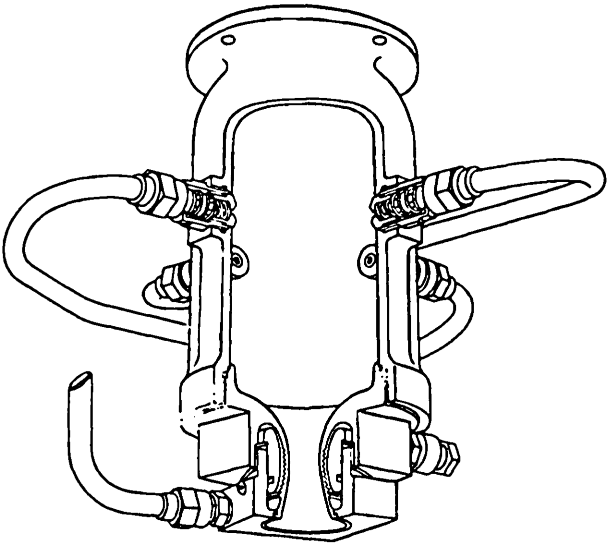

Figure 3 Chamber of the ORM-50 engine, 1933

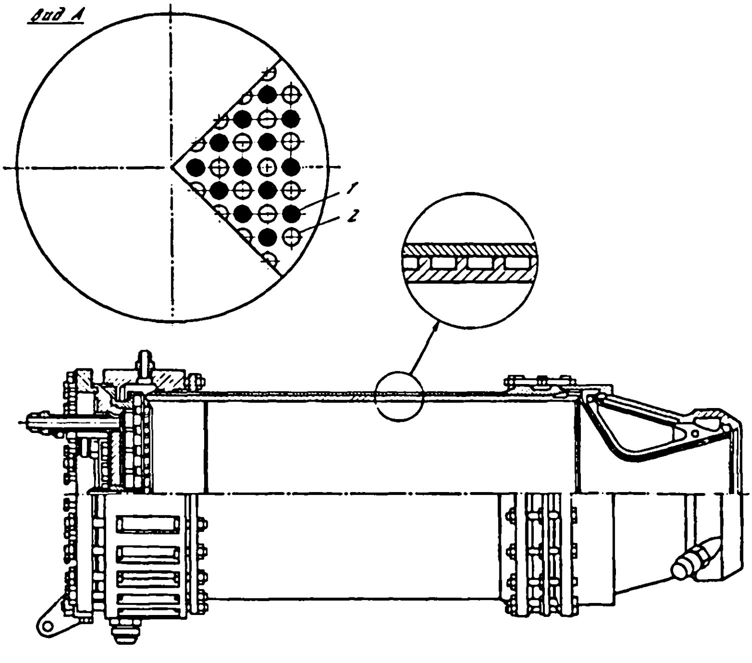

Figure 4 Chamber of the RD-1M engine, 1946. Placement of the injectors in the head (view from the side of the nozzle): (1) oxidizer, (2) fuel.

The ORM-50, ORM-52 and subsequent LPRE's developed by the group under the supervision of Glushko in the 1930's operated on a two-component propellant in which the oxidizer was nitric acid and the fuel was tractor kerosene. These cheap products were widely used in the economy and did not cause as much inconvenience in use as liquid oxygen and even more so hydrogen. It is important to note that, although in theory, according to the specific impulse, fuel with a nitric acid oxidizer is worse than oxygen, in fact, Glushko's engines turned out to be more efficient than all the others. This is explained by the fact that the GDL group managed not only to solve the problem of reliable cooling of the chamber, but also to ensure a high-quality fuel mixture atomization, i.e., a good intermingling of the atomized fuel components. Thus, the properly prepared mixture burned at a pressure of 20-25 kg/cm^2, which was a record for that time. Upon leaving the nozzle, the combustion products expanded to the normal atmospheric pressure. As a result, the specific impulse amounted to 2,110 m/s.

The design solutions contained in the ORM-50 and ORM-52 were developed further in the Soviet LPRE's developed towards the end of the Patriotic War [World War II]. Among them was the USSR's first mass-produced LPRE, the RD-1 (in the final version it was called the RD-9Z), designed by Glushko and produced by an experimental unit in a quantity of more than 200 copies [6]. This engine, which underwent static tests, developed a thrust of 300 kg and had an operational life of 1 hr., which was limited by the wear and tear on the fuel pumps. They were power-plant driven pumps. These pumps were used on the domestic LPRE's first and cut down greatly on the size of the fuel tanks. The RD-1 was intended as an auxiliary aircraft engine to supplement the basic (piston) engine unit.

During the war, in the JPSRI, they also developed an LPRE for the basic power plant of the BI series aircraft. This LPRE, with a thrust of 1,100 kg, designed for forced feeding of a nitric acid-kerosene, at first did not satisfy the given technical requirements, and the main reason here turned out to be the not completely successful design of the chamber, which did not provide adequate cooling and high-quality fuel mixture atomization. A.M. Isayev, one of the inventors of the BI aircraft, himself undertook to redo the engine, and as a result of the creative use of all domestic experience, this talented designer managed to develop a reliable LPRE with a high performance level. It was called the RD-1 (i.e., the same as Glushko's engine) [7, pp 24-31].

In 1946, A.M. Isayev improved his own engine, having increased its operating life to 1 hr. and having lowered the hydraulic losses in the lines (for the purpose of reducing the feed pressure). The chamber of this modified engine, the RD-1M, contained a head with dozens and dozens of injectors, placed in a "chessboard" arrangement (Figure 4). At the same time, the outermost oxidizer injectors sprayed the liquid towards the center of the head and at the corners of the chessboard were fuel injectors with increased flow rates [7, p 34]. Thus, the chamber wall operated not only at a lowered temperature, but in a reducing medium, which was an additional guarantee against a burnthrough. The numerous injectors, placed evenly on the cheese head (in the first version of the RD-1 the head was reminiscent of the shape of a marquee), ensured a good intermingling of the fuel components; however, because of the intensive curtain cooling (which disrupted the homogeneity of the mixture), the specific impulse of the LPRE was reduced by 60 m/s and amounted to all of 1,920 m/s. Subsequently, they were able to reduce this shortcoming in the new fuel mixture atomization system to a minimum, and the technical ideas, tested in the design of the RD-1M's injector head, were widely used in Soviet LPRE's.

The designs of the LPRE's developed during the war years reflected to a large degree the level of aviation engine production of that time. Their parts were based on the same technological equipment as the parts for piston engines. The chambers of the LPRE's used up quite a bit of labor in their production and they required a skilled work force. For example, in order to get the internal wall with ribs, a lathe operator had to carve out the complex shaped surfaces and to cut in them 16 and 24 starting threads. Just like piston motors, the LPRE designs were made as teardownable items with numerous connecting parts. In order to seal the end joints between the internal and external walls, which move relative to one another during operation due to unequal heating, it was necessary to install compensators in the form of bellows, self-sealing lead gaskets, and so on. For reasons of durability, the chamber parts had to be made of steel and made large. It is true that the use in one of the German aviation LPRE's (the BMW 109-718 engine) of a head built according to the same principle as that of the RD-1M, made it possible to make widespread use of a lightweight duralumin alloy. However, the specific impulse of this LPRE amounted to only around 1,750 m/s -- which is approximately 200 m/s less that that of the RD-1 designed by Glushko [8, p 348].

Along with the aviation LPRE, the great technological achievement of the 1940's was the powerful LPRE developed in Germany for the A-4 ballistic rocket with a range of nearly 300 km. The chamber of this engine, which operated on a liquid oxygen -- aqueous solution of ethyl alcohol propellant combination developed a thrust of up to 29 tons. The specific impulse of the LPRE amounted to 2,280 m/s with an initial combustion products pressure of 15 kg/cm^2. A high-quality fuel mixture atomization in the chamber was achieved thanks to the head with the so-called pre-combustion chambers -- sleeves with injectors in the bottom and in the conical walls. Individual jets of the mixed fuel, entering the combustion area from the pre-combustion chambers, became mixed among themselves prior to combustion (Figure 5). Among a number of other elements, the pre-combustion chambers had been invented several years before the beginning of the A-4's development. The various versions of them were described, for example, in the book by G.E. Langemak and Glushko, published back in 1935 [9, pp 91-97]. The engine chamber of the A-4 rocket was peculiar in that it was produced from smooth (non-ribbed) sheet metal shells, which formed the external and internal walls, which were joined into a whole by welding over several hoops. At the same time, a section of the hoops had openings for feeding fuel from the cooling system into the gas stream for the purpose of creating a cooling curtain.

In comparison with the aviation LPRE chambers, such a design was a step forward. However, by the second half of the 1940 decade, its limited possibilities had become clear. During the indicated time period, in the USSR and abroad, research work had begun that was aimed at the development of rocket boosters capable of covering distances of thousands of kilometers, and later of completing flights into space. Calculations indicated that based on the technological level attained in the A-4, in order to launch a satellite with a mass of several kilograms, it would be necessary to have a five-stage rocket with a launch mass in the hundreds of tons (see, for example, [10]). In order to seriously talk about the goal set, it would be necessary to increase the specific impulse of the LPRE by a factor of approximately 1.5 and reduce (at the least, by half) the mass of the engine and all the other rocket components.

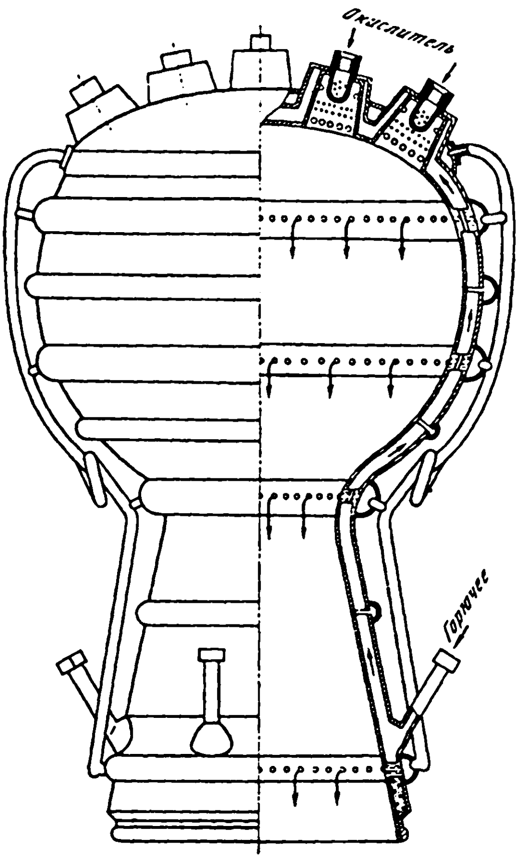

Figure 5 Engine chamber of the A-4 rocket, 1942

Work in this direction was begun in our country in 1946-1947 by the Experimental Design Bureau of the GDL [GDL-EDB], headed by Glushko. The project studies (see, for example, [11]) indicated that the required specific impulse of the LPRE could be attained by using a liquid oxygen -- kerosene propellant combination together boosting of the operating pressure in the combustion chamber up to the level of 50 kg/cm^2. At the same time, however, it was necessary to thicken the external wall of the chamber and the mass of the chamber increased substantially. Indeed, the problem of cooling the chamber seemed to be unsolvable.

The fact is that in comparison to the A-4's engine, the initial temperature of the gas in the chamber was increased by 900 K and the density of the heat flux increased by a factor of three. In order to cool the combustion wall, in accordance with the laws of heat transfer, it was necessary to make it very thin. But then it would be crumpled by the pressure of the fuel flowing in the regenerative cooling system. It would be possible to reduce the heat fluxes by intensification of the curtain cooling, but this reduction would be attained at the cost of a reduction in the specific impulse.

As in many other instances, the prerequisites for the solution of the problem that had arisen were contained in the early developments of rocket technology's pioneers. Let us make a small excursion into the history of the LPRE. In 1933, in the GDL, the ORM-48 LPRE was designed with a nozzle made from the ribbed steel wall and a copper jacket, which were joined into a single whole by soldering [12, p 11]. The soldering was done using a hard solder along the tops of the spiral ribs made on the steel wall (Figure 6). Thus, closed conduits were obtained for the passage of the coolant. Ordinary water was used for this and the ORM-48 engine itself was intended for experiments to determine the nature of the gas pressure change along the nozzle.

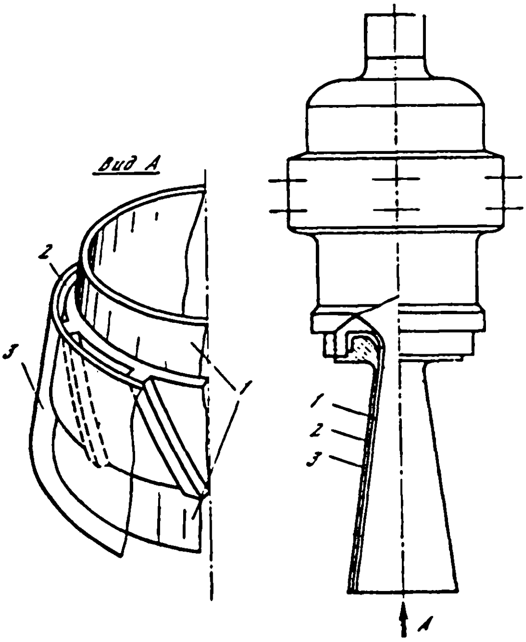

Figure 6 The ORM-48 engine, 1933. Nozzle section: (1) combustion wall, (2) band of ribbing on the combustion wall, (3) jacket.

In the middle of the 1930's, chambers with integral bodies of various design were also developed by E. Sänger in Germany. In 1934, he tested (and a year later patented) a chamber with a body made of winding copper tubes, joined together with solder, and a chamber close in design to the ORM-48. The body of the latter contained a bronze internal wall with milled ribs to which the jacket parts were soldered on the outside [13, pp 236-237].

Veterans of rocket technology remember that, at the end of 1942, chambers with whole bodies interested Isayev. Over the course of 1943, under his supervision, nozzles were designed, similar in design to the nozzle of the ORM-48, as well as a furnace for soldering, equipped with a heating air-kerosene burner and a system for developing a reducing hydrogen medium. By the end of 1944, approximately 10 nozzles had been produced in this furnace. All this work was due to the burnthroughs of the BI aircraft's LPRE chambers. Isayev discovered the reason for the burnthroughs in the deformation of the chamber's combustion wall, which led to a local increase in the space between the walls and a reduction in this place of the velocity of coolant. However, with the development of the RD-1, the chamber of which did not burn through, the work on soldering came to an end. (In addition, Isayev's small group could not produce the sufficiently large furnaces necessary to solder the entire chamber.)

At the end of 1944, Isayev's group tested a chamber, the cylindrical portion of which was produced from two sheet metal shells, welded along the ends. The space between the shells was fixed using longitudinal wires placed inside, which were welded along the ends of the shells. After several launches at a reduced operating level, this chamber lost stability and burned through at a 90 kg thrust level [7, p 38]. Nevertheless, the work on chambers made from sheet metal material continued, inasmuch as the fate of the EDB's subsequent plans depended to a large degree on their result. Isayev recalled later [7, pp 41-42]:

> "If the EDB had had a good production base available, and its workers had a good idea about the possibilities for well set-up mass production with a high level of technology, it is probable that their designs would have been different. But the EDB workers ... had available a very small number of general-purpose machine tools, the simplest welding equipment, they experienced difficulties with the forge shop and in general they did not have a foundry ... Every production order was pinched to the minimum and fulfilled late. Therefore, the designer's first task was to achieve maximum simplicity and to develop a design which would not require special equipment, would be produced from on-hand materials and did not require exploitation of new technological processes. Simplicity ... as it seemed, yielded also reliability in operation".

They managed to develop an operationally capable sheet metal chamber after a head with curtain cooling injectors was worked out. The heat fluxes, recorded during the operation of chambers with this head, turned out to be so low that the designers decided to weld a jacket to the combustion wall over the entire surface with spot welding through connecting bands. They constructed the injector head on the form of a block made from three bottoms (which formed collectors for the oxidizer and the fuel), joined by welded seams. The internal and middle bottoms were joined, in addition, through laminated tubular injectors for the oxidizer (Figure 7) [7, p 43]. Tests of the chamber with this design (U-1250) took place in the summer of 1946. At a pressure of 17 kg/cm^2, a thrust of 1,300 kg and a specific impulse of 2,050-2,090 m/s were obtained. This gave Isayev's group a reason to plan a whole series of similar chambers with thrusts in the range of 400-9,000 kg, an operating pressure of 16 kg/cm^2 and a specific impulse of 1,960-2,110 m/s. It was proposed that the LPRE's with these lightweight chambers, intended for pressure-feed of a nitric acid-kerosene fuel, would satisfy all the needs of the developing rocket technology, beginning with aviation engines up to engine units for long-range rockets [7, pp 50-52].

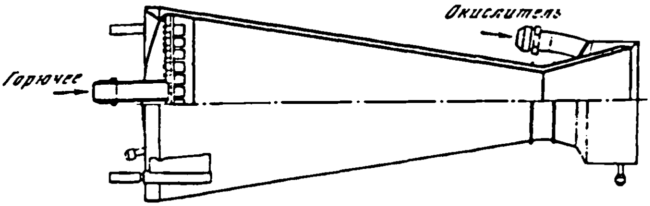

Figure 7 The U-1250 engine chamber, 1946

Having noted the erroneousness of such a point of view, it is necessary to point out, however, that the chambers with a weld design, developed by Isayev's group, hastened the development of contemporary designs, which are capable of operating under conditions of high pressures, temperatures and heat fluxes, developing a high specific impulse in the absence of limitations on a practical introduction of chambers with firmly interconnected shells was the danger that such chambers would fail because of thermal stresses arising as a consequence of the large difference in the temperatures of the two shells. Isayev's welded chambers aided in overcoming this danger to a significant degree.

In 1948, the GDL-EDB group made plans for chambers in which the ideas outlined in the design of the ORM-48 and subsequent Soviet LPRE's were realized on a contemporary technological level. In these chambers, the joining of the walls was accomplished using a high-temperature solder along the tops of the ribs milled in the combustion wall. The chamber heads had multilayer bottoms with injectors soldered into them. At the final stage of the chamber production process, the individual sections of the body and the head were welded into a single whole with circular seams. As a result, an integrated soldered-welded design was obtained (Figure 8) [14, p 12]. In such a so-called design with frequent connections, the walls could have a small width, since, thanks to the numerous thin ribs, the individual conduits obtained for the passage of the coolant were narrow. Thus, the combustion wall could be produced from a relatively flimsy, but still highly heat-conductive copper alloy, and the jacket from highly durable alloys, for example, alloy steels.

Tests of the first of the new design chambers took place in the GDL-EDB in mid-1949. These chambers, which operated on an oxygen-kerosene fuel and developed a thrust of 7 tons with an initial gas pressure of 60 kg/cm^2, were intended for development of technological processes and also for research on questions concerning cooling and fuel mixture atomization. At the same time, in an experimental chamber of similar design with a thrust of 50 kg, prospective rocket fuels were tested. The GDL-EDB, jointly with specialized SRI's, conducted expanded research in the field of the technology of soldering layered designs made from homogeneous and heterogeneous materials. As a result, a method was worked out for vacuum soldering of chamber joints in a neutral protective medium (nitrogen). In order to obtain quality solders of the joinings, the experimental production unit of the GDL-EDB drew up plans for and produced special electric furnaces, which provided high speed heating, a small drop in temperature during the process of loading the joints and a constant temperature during the soldering process. For the combustion wall, it was necessary to develop a special heat-resistant alloy (chromous bronze) which combined high thermal strength and operating properties. Also exploited were new types of rustproof and alloyed steels and a new solder based on silver and copper was developed which ensured a high degree of heat resistance for the soldered joinings and so on [15].

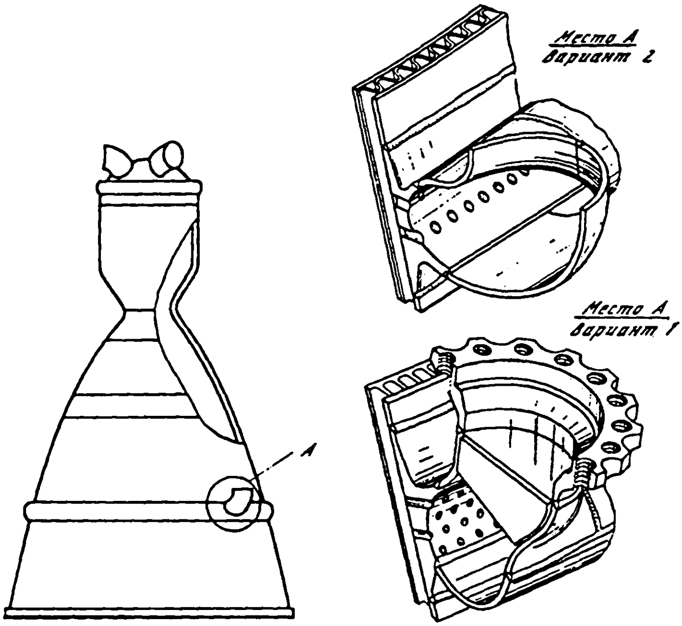

Figure 8 Soldered-welded chamber designed by the GSL-EDB

In addition to the chamber with a ribbed internal wall, in the GDL-EDB they developed a design version with smooth shells, connected using a middle corrugated wall. It can be produced, for example, from copper alloys or well stamped low-carbon steels. Such a design, much simpler to produce, is based on less stressing operating conditions. For example, in the combustion area and in the area of the nozzle throat, the connection between the walls can be accomplished using ribs and at the exhaust section of the nozzle, where the heat fluxes are not as intense, using corrugation. The research conducted in 1954 on chambers with soldered-welded designs and the experience obtained during the production of the large, full-sized joints were important factors in the successful development of the RD-107 and RD-108 engines, which ensured space flight in 1957. In each of the 20 basic chambers of the five LPRE's of the Sputnik launcher, nearly 70 kg of high-caloric oxygen-kerosene fuel was burned in 1 sec. At the same time, gases were formed with a pressure of 50-60 kg/cm^2 and a temperature of 3,500 K, which then dilated in the nozzles to 0.3-0.4 kg/cm^2, speeding up to nearly 3,000 m/s. The chamber developed a thrust of 23 tons with an all-up mass of only 143 kg; the length of the entire chamber was 1.9 m, the diameter of the nozzle at the exhaust point amounted to 0.72 m and the combustion chamber to 0.43 m. In each liter of volume in the combustion area, there were up to 10 MJ of heat per second and the density of the heat flux entering into the wall of the chamber amounted to 17 MWt/m^2. Under these conditions, without the adoption of special measures, the design would burn up in the computed seconds.

With the development of the chambers with a soldered-welded design, there appeared broad possibilities for increasing the LPRE's specific impulse by increasing the operating pressure and using efficient rocket propellants; along with this, there was a substantial reduction in the relative dimensions and in the specific mass of the engine (the mass of the design per unit of thrust). The indicated measurements to a specific degree are illustrated in Figure 9, in which the chamber of the A-4 rocket is represented in comparison to the soldered-welded chambers of the GDL-EDB designs for the period 1957-1962.

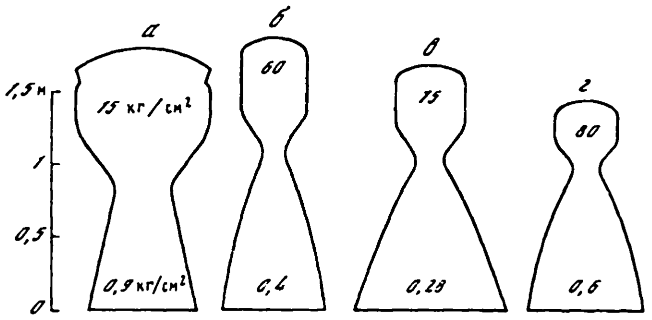

Figure 9 The chambers of various LPRE's. (a) the A-4 rocket chamber, 1943 (thrust - 28 tons, specific impulse - 2,300 m/s, mass - 450 kg); (b) RD-107 chamber, 1957 (23 tons, 3,141 m/s, 143 kg); (c) RD-219 chamber, 1961 (45 tons, 2,898 m/s, 127 kg); (d) RD-111 chamber, 1962 (41 tons, 3,157 m/s, 136 kg).

A high operating pressure and an efficient rocket fuel were necessary conditions but not sufficient for obtaining a high specific impulse. No less important was the need to reduce to a minimum the energy losses (in friction, heat transfer and so on) in all phases of the chamber's operating process, including the atomization of the fuel components by the injectors, their mingling, combustion and the subsequent expansion of the gases formed in the nozzle. This difficult task was solved by the joint efforts of designers, technologists and scientists, specialists in the various fundamental sciences. Their cooperation was an important factor in the development of an LPRE, which was supported by the development of the design of so substantial a part of the chamber and the entire engine as the jet propulsion nozzle.

The LPRE's of the 1930's and 1940's were intended to operate in the lower layers of the atmosphere. Therefore, their nozzles were designed for the expansion of the gases to a pressure, equal or close to that of the normal atmosphere. The relatively low thrust values and the low degree of gas expansion made it possible to use conical nozzles with small expansion angles. These nozzles were simple to produce, had relatively small dimensions and mass and were characterized by small energy losses in the gas stream. Nevertheless, even at the beginning of the 1930's, in the GDL-EDB, there were proposals for more improved nozzles -- ones with profiles which would ensure the same degree of gas expansion as the conical ones, with a shorter length. The indicated proposal was the result of experiments set up in 1930 for the purpose of determining the optimum parameters for the chamber's operating process and the geometric characteristics of the nozzles: a powder engine, equipped with two different nozzles, installed diametrically opposite one another, was suspended on a differential pendulum and tested [5, pp 103-109].

During the development of the first space LPRE's (the RD-107 and RD-108), in which gas expanded from a pressure of 50-60 kg/cm^2 to 0.34-0.40 kg/cm^2, the use of curved nozzles of relatively simple configuration -- shaped like arcs of circles, yielded a notable gain in axial dimensions and engine mass. From the beginning of the 1960's, in the GDL-EDB designs (the RD-119 with a gas expansion from 80.5 to 0.063 kg/cm^2 and the RD-219 -- from 75 to 0.28 kg/cm^2), they began to use nozzles with an angular inlet (into the supersonic part), that were suggested by the JPSRI jointly with the USSR Academy of Sciences' Computer Center. The development in the GDL-EDB (jointly with the aforementioned center) of nozzles with an experimental profile aided in the further improvement of the LPRE's characteristics. Such nozzles have been used, in particular, in the RD-111 and RD-253, where the operating gas expanded from a pressure of 80 to 0.5 kg/cm^2 and from 150 to 0.62 kg/cm^2, respectively [16, p 16].

In researching the problem of the selection of the optimum parameters for the operating process, the GDL-EDB specialists turned their attention to the circumstance that an increase in pressure would lead to a reduction in the dimensions of the chamber. The given circumstance was an additional factor which determined that the development of LPRE's would be in the direction of boosting the operating process. On this path, the school of rocket engine production, which was associated with the activities of the GDL-EDB, undoubtedly occupied a leading position [16, p 15]: over the 10-year period, which concluded with the development of the first space engines, the pressure in the chambers of the powerful LPRE's increased by a factor of 4, and in recent years -- by the same amount again. The engines of the first half of the 1960's operated with combustion chamber pressures of up to 75-80 kg/cm^2 (in the rated mode). With the development in 1965 of new engines (for example, the RD-253 for the Proton rocket boosters), this indicator increased two-fold at one stroke.

Chambers with a pressure higher than 100 kg/cm^2 have the peculiar feature that the fuel components enter into their combustion area in a different aggregation state: usually liquid fuel from the regenerative cooling system and the exhaust generator gas, which represents the products of the combustion of the oxidizer with part of the fuel. The latter is produced in a special unit -- the gas generator, and is used to drive the turbines, which turn the centrifugal fuel pumps (the turbines together with the pumps form a turbopump unit). In chambers with pressures up to 100 kg/cm^2, instead of exhaust generator gas, liquid oxidizer flows to the injectors: the post-turbine gas is discarded into a separate exhaust pipe. The transition with the increase in pressure from the "liquid-liquid" system to the "liquid-gas" system or the system with afterburning of generator gas is explained by the condition of balance between the capacities of the fuel pumps and the turbine. In accordance with this condition, with the increase in pressure in the chamber (and, consequently, the fuel feed pressure), an ever increasing part of the fuel is supposed to be used to obtain the generator gas, and its disposal in an exhaust pipe becomes a disadvantage since it leads to a reduction in the result specific impulse of the LPRE.

The necessity of afterburning of the generator gas, like the subsequent chamber pressure increase, did not require principal changes in the soldered-welded design of the chamber developed for the first space LPRE's. They improved and altered only individual parts, materials and technological processes (in particular, substantial changes were endured in the soldering process and the corresponding technological equipment). The use of the latest achievements in the field of the general metallurgy, weldings, thermal process soldering and gas dynamics, along with the results of purposeful scientific research and the accumulated design experience made it possible to realize the merits of the soldered-welded design of the chamber to an ever greater degree. An idea of this can be obtained from an examination of Figure 9 and the following data on the chambers of the RD-216 and RD-253 engines.

The first of the indicated LPRE's, developed in 1960 (and used since 1964 in the Cosmos and Intercosmos rocket boosters), uses a non-afterburning system; the second, developed 5 years later, belongs to the family of engines with afterburning. In both LPRE's, one type of fuel is used (in the RD-253 one with a higher calorific value). They develop an identical thrust on the ground (150 tons), which is created in the RD-253 in a single chamber with a mass of 400 kg, while in the RD-216 it is done by four identical chambers with a total mass of 508 kg. With a substantially greater thrust, the RD-253 chamber is characterized by the smaller dimensions of the combustion area: diameter of 430 mm and length of 238 mm compared to 480 and 300 mm for each chamber of the RD-216. With regards to the specific impulse, the RD-253 chamber significantly exceeds the RD-216 chamber: by 326 m/s during operation on the ground and by 210 m/s in a vacuum.

During the development of the chambers for the RD-216 engine, which contain combustion products with a pressure of 75 kg/cm^2 and a temperature of 3,050 K, it turned out to be possible to use the most simple version of the soldered-welded design: the steel shells of the chamber are joined using corrugated spacers (aligned in the subcritical part of the nozzle spirally -- for the purpose of intensification of the regenerative cooling). The peripheral injectors, through which part of the fuel flows into the combustion chamber, are used to set up the internal curtain cooling.

In the RD-253, the chamber operates under immeasurably more stressful conditions than in the RD-216, which is explained by the substantial increase in thrust along with the decrease in the dimensions of the combustion area, and also the increased pressure (150 kg/cm^2) and temperature (3,400K) of the combustion products. Regarding the degree of stress of the operating process in the chamber of the RD-253, this can be judged by the following indicators: more than 350 g of fuel are dispersed each second across 1 cm^2 of the cross-section of the combustion chamber (seven to eight times more than in the RD-107 and RD-108), and a 1 cm^3 section of the combustion area produces nearly 5 tons of thrust (13 to 15 times more than in the first space engines). The density of the heat flux entering into the wall of the RD-253's chamber amounts to 120 MWt/m^2. Under such stressful conditions, the corrugated spacers can be used only in the structure of the exhaust section of the nozzle, which is the least loaded section with respect to heat. In the remaining section of the chamber, an internally milled wall, produced from highly heat-conductive bronze, is used. The indicated wall is protected from burnthrough by the liquid gas film formed by the fuel entering into the combustion area from the regenerative cooling system via two rows of openings. In addition, (by means of spraying), a high-temperature, heat-insulating coating of zirconium dioxide has been deposited on the internal surface of the bronze wall. In this connection, it must be remembered that refractory compounds based on available ceramics had been developed and successfully used in experimental chambers of the GDL-EDB back at the beginning of the 1930's [5, pp 78-95].

Since the time of the development of the first space engines, the soldered-welded chambers designed by the GDL-EDB have formed the basis for the domestic LPRE's. These lightweight, compact units operate under pressures in the hundreds of atmospheres, endure temperatures of 4,500 K and are resistant to the effects of any chemically corrosive products [17, p 20]. Thus, thanks to the development of ideas contained in the works of the pioneers in cosmonautics and the technical solutions realized in the early designs of the LPRE's, space flight became feasible, as did the subsequent successes of Soviet cosmonautics.

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