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Chapter 6

Engines for First Space Launch Vehicle*

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Abstract

The space era of mankind began October 4, 1957. The first artificial Earth satellite was launched on this day. As you know, this launch was carried out by an R-7 launch-vehicle, which used RD-107 and RD-108 liquid-propellant rocket engines developed by OKB-456 (now NPO Energomash) under the leadership of chief designer V. Glushko. The basic version of these engines for the first and second stages of R-7 rocket was developed in 1954–57. The original design of the multi-chamber engine became the basis for subsequent modifications.

Over 60 years, space launch-vehicles of Vostok, Voskhod, Molniya, and Soyuz famous family are in active operation and all this time the engines developed by NPO Energomash operate reliably. More than 10 modifications of engines for the first and second stages have been developed over the years for various space missions. Since 2001 new modifications of RD-107 and RD-108 engines—14D22 and 14D21 engines—are used in composition of Soyuz LV. These engines, like the previous ones, are based on the design of their famous predeces-

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sors, but they provide an increase of engine operation stability and increase of specific impulse of engines, which ensures increase in the payload mass.

We continue efforts on further improvement of this family of engines. The major work on engine modification and supervision of its serial production, as well as flight operation is performed now in the Privolgsky branch of NPO Energomash in Samara. Significant support and assistance in these efforts is provided by specialists of NPO Energomash (Khimki). Serial production of engines for many years was carried out at JSC "Motorostroitel" (formerly "Plant named after M. Frunze"), Samara. After some reorganizations, this company received a new name JSC "Kuznetsov." This chapter outlines the history and features of main modifications of engines used in composition of the R-7 launch-vehicle family.

Engines for First Space Launch Vehicle

The beginning of the space era was marked by the launch of the first artificial Earth satellite due to creation in the USSR of the now well-known R-7 rocket. At that time it was the world's most powerful rocket. It was developed by several design bureaus that were created mainly after the Second World War for development and modernization of German rocket technology, primarily A-4 (V-2) missiles.

The creation of the R-7 rocket was an outstanding achievement of human mind and scientific and technical capabilities. Engines developed with a high degree of reliability in Special Design Bureau-456 (OKB-456, later—Energomash), headed by Valentin Glushko, have played a key role in development of this rocket.

After development of the RD-103 engine (based on the A-4 missile engine) for the R-5 rocket with a range of 1,200 km, Glushko's OKB started development of the engine for the R-7 intercontinental ballistic missile. Achieving such a range, required the creation of a new type engine, operating on a more efficient rocket propellant.

The selection of propellant came from the fact that for existing oxidizers the highest specific impulse could provide only liquid oxygen. Fuel had to be more calories than the alcohol, and also well mastered. Kerosene was such a fuel. It ensured on thermodynamic characteristics a sufficient level of profitability, but its use as a fuel for rocket engines caused the need to overcome serious difficulties: temperature of its combustion with oxygen was at nearly 1,000 degrees higher than with water solutions of alcohol, while cooling properties were much worse. Namely, fuel has to cool the walls of the chamber if oxygen is the oxidizer. The task of cooling was complicated by the fact that for optimum engine performance, it was necessary to increase chamber pressure, at least by two times in comparison with reached pressure of alcohol engines.

Fundamentally a new chamber design was required for the new engine. It was a combination of a thin, not load-bearing, but highly heat-conducting wall and steel load-bearing wall, and a new type of wall connection. Specialists of Glushko Design Bureau created such a design. Its basis—a wall of copper sheet with a thickness up to 6 mm; with ribs at the outer surface of the wall. The grooves between ribs are intended for the flow of cooling fluid. The outer surface of the copper wall ribs is brazed with the steel wall. The ribs improve heat transfer from walls. A thickness of 1 mm remains on the grooves bottoms. The main features of chambers are the same, up to the present time, in almost all domestic Design Bureaus.

By the end of 1948, the KS-50 ("Lilliputian" or "Midget") first experimental chamber of the new type was developed and tested on the fire stand.

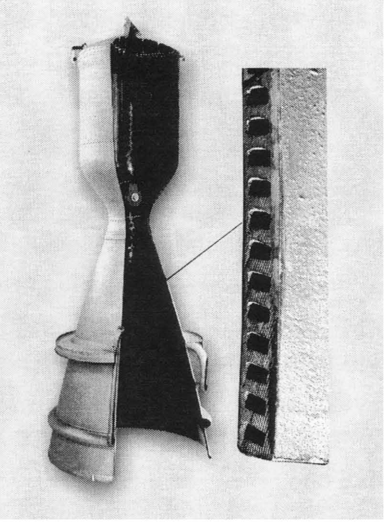

Figure 6–1: Combustion chamber with cooling duct. (NPO Energomash).

The AD-140 experimental chamber with a thrust of 7 tons was the next step in development of basic structural elements of the chamber of the future powerful engine. The AD-140 cylindrical combustion chamber had a diameter of 240 mm, which was chosen from conditions of simulation of parameters and characteristics of structure. It was used for testing at a pressure of 60 atmospheres for selecting the best mixing elements with maximum possible combustion efficiency. It was checked and for other units, for example, new belt slotted screens for fuel film cooling on inner surfaces of the wall of the chamber.

It was found that a flat firing bottom with injector elements, the axis of which is parallel to the axis of the chamber, is optimal for a cylindrical chamber. It is possible with minimal losses to organize optimal mixing of propellant and wall cooling in such a design.

In May 1954, OKB-1 sent to OKB-456 a draft of specifications for development of engines of one and two stages. Five single-chamber engines (four engines for the first stage and one engine for the second stage) were proposed for development of the propulsion unit as a basic version. LV control was carried out with gas-jet rudders on the first stage and only for the second stage the development of two variants was proposed: with gas-jet rudders or with steering chambers with feeding from the main turbopump.

OKB-456 sent, on June 15, 1954, a revised version of specifications for final approval in OKB-1. In these specifications, OKB-456 proposed development of main engines in two versions: single chamber and four chamber. OKB-456 prepared a draft project of development of engines of one and two stages.

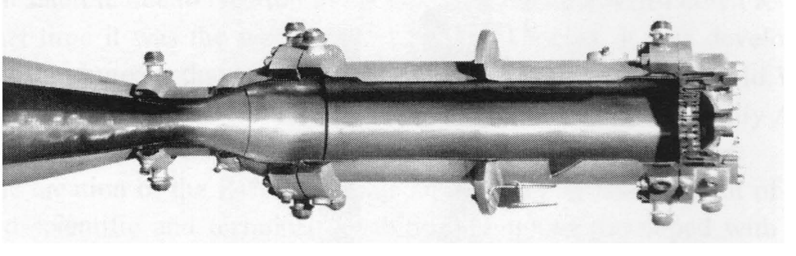

Figure 6–2: Experimental chamber AD-140. (NPO Energomash).

Specifications for development of the engines in versions proposed by OKB-456 were approved by S. Korolev on July 4, 1954, with the four-chamber engine option as an alternative one.

However, in the process of detailed study of possibilities of technological development of both engine versions, specialists of OKB-456 came to the conclusion that a single-chamber engine would not be made in the government established schedule. Unique large equipment tools were required for manufacture of the chamber. Such equipment did not exist. It was needed to design and produce such equipment to obtain the required parameters and characteristics.

The first reaction of V. Glushko and S. Korolev on such a conclusion was negative, but the hard schedule of R-7 development predetermined the choice of the engine variant in favor of a four chamber version. Simultaneously with choice of the main engine, a design for the rocket flight control unit was defined—steering chambers were selected.

S. Korolev and his team understood the difficulties of engine builders regarding overcoming high-frequency oscillations and agreed to a four-chamber variant of main engines, and went to overcome by joint efforts the difficulties of simultaneous controlled start-up of five main engines propulsion systems, comprising a total of 32 chambers (20 main and 12 steering ones). On the other hand, in the absence of restrictions on engines diameter a reduced engine height due to multi-chamber option had significantly shortened the rocket.

The M. Melnikov division of OKB-1 developed steering chambers under base of existing experimental chamber. They had also a test stand for autonomous tests of such chambers.

In the first phase of fire tests, firing weak points in the design were identified—burnouts in the throat section, inner wall thinning, etc., were eliminated. About 500 fire tests on 285 steering chambers were conducted up to spring 1957. But the final tests of steering chambers in conjunction with main engines needed to take place at the fire stand of OKB-456.

The second phase of steering chambers tests was their joint tests with RD-107 and RD-108 engines at stand #1 of OKB-456. During these tests, it was found that high frequency pressure pulsations occurred in steering chambers in preliminary mode, and in transition to main mode there is a sharp decrease of mode and pressure pulsation, leading to burnouts of firing bottom of mixing head.

To eliminate these phenomena, under proposal of OKB-456, a new scheme of propellant feed to steering chambers was introduced with positive results. Subsequent tests in composition of the propulsion unit, and then in the whole "package" (five propulsion units together) have confirmed the effectiveness of the new scheme of propellant feed of steering chambers.

The final conclusion about approval of a system of steering units for flight tests in the composition of the R-7 was approved on March 15, 1957, by chief designers of OKB-1 and OKB-456, S. Korolev and V. Glushko.

In 1957, when development of the RD-107 and RD-108 engines was in the final phase and in accordance with existing agreements, OKB-456 designers began to improve the steering chambers design to increase life resource of chambers with elimination of burnouts of the inner wall and to use more advanced technology. A new design of steering chamber has high reliability in terms of combustion stability and cooling, and higher specific impulse (about 15–20 sec. higher) in comparison with variant developed initially in OKB-1.

The first production sets of D166-000 steering chambers were manufactured at factory #456 in Khimky, then their production was transferred to a new engine production plant #224 in Kuibyshev (now Samara). At Yuri Gagarin spaceflight steering chambers of OKB-456 design were used.

After completion of a brief excursion into steering chambers history, let us go back to development of the main engines of the R-7. In 1954 schematic and layout of the R-7 two-stage rocket, its blocks and propulsion units were mainly decided.

The main chamber was created for a pressure of combustion products of 60 atmospheres, without special margin not only in strength (to avoid overweighting), but also on tolerance interval for pressure of lower border of high-frequency instability. The inner diameter of the cylindrical part of the combustion chamber (430 mm) was determined on the basis of tests on the limit proven level of specific flowrate intensity—second propellant consumption per unit of mixing head area in relation to chamber pressure.

The turbopump characteristics were defined based on the need to ensure the gas pressure in the main combustion chamber and feed of propellant to steering chambers. Along with fundamental technical solutions the issue of design and technological documentation was conducted, production preparation took place, and the required test facilities have created. A finished work plan was made and works were conducted around a broad front.

Ensuring the operability of the chamber was the most difficult part of the work. Chamber fire tests began in 1954. The first tests gave positive results. Tests began on experimental engines having one, two, and then four combustion chambers.

However, due to the complexity of the simultaneous launch of five engines with 32 chambers, it was decided to create a special stand for tests of joint start-up of engines and to ensure stable combustion in chambers in preliminary mode for selection of sensors monitoring progress of start-up and parameters level. This stand was created near a main fire stand. In total, there were about one thousand engine start-ups without subsequent transfer to main mode.

Simultaneously with tests of start-up, tests of the chamber in main mode were conducted. In this phase, basic two-component injector elements were optimized in terms of choice of length of zone of components pre-mixing. By this time all units of nominal engine successfully completed individual tests on special stands in conditions, close to real ones.

In the beginning of 1955, a first test of a full, four-chamber engine was conducted. Since the beginning of nominal engine tests we had serious trouble: in process of transition from preliminary mode to main mode the high frequency oscillations of destructive intensity were developed in chambers. Our designers made a change in characteristics of opening of the oxidizer main valve. An updated valve gave the desired results and the modified design of the oxygen valve is preserved forever.

During final development of the engine in main mode we also had problems with ensuring combustion stability. Acceptable levels of protective near-wall zone for chambers of RD-107 and reduced level, with a corresponding increase in specific impulse, for chambers of RD-108 that was possible due to lower nominal combustion pressure, was found. Because of this the chambers of two engines are not unified by a mixing head.

The most important joint development work was a ground test firing of propulsion units in composition of separate blocks—lateral and central, and then a package of all blocks, i.e., the rocket in whole. For these works a unique stand was created, at the time, apparently, the world's largest, on site of rocket industry test institute, now known as NITs RKP (former NII KhimMash).

Tests of the lateral block were conducted initially. A propulsion unit and all systems of stand confirmed its efficiency. This important milestone was passed in 1956. The engine did not require any modifications. Further, per approved program test of package (five blocks) was carried out successfully, opening the way to flight tests.

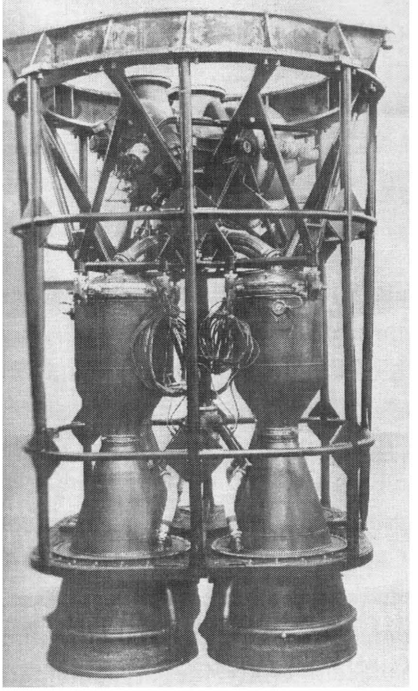

Figure 6–3: Four-chamber modification of RD-107 engine. (NPO Energomash).

During the first launches of R-7 missiles in 1957, only once, during the first launch on May 15 an emergency took place, perhaps, due to the engine: in the tail section of one of the blocks a fire started which to 98th second of flight led to the need of emergency termination. The place of the leak occurrence remains unknown—in engine or in rocket lines. Effective measures to ensure reliable leak tests were made in all plants and technical positions.

Senior leadership of our country authorized the preparation and launch of satellites under initiative of S. Korolev, V. Glushko, N. Pilyugin, Board of Chief Designers and USSR Academy of Sciences.

Special engines were made for these launches. At first, all margins were calculated and the weight of the first satellite was limited to 85 kg, engines were used with increased by two units of specific impulse, and it was decided that the engine in the central unit, i.e., in the second stage, shall be operated until a special signal about end of one of propellant components, which required additional development tests. Engines and rockets have received in its designations additional letters "PS"—"simplest satellite."

The launch of the first artificial Earth satellite was conducted on October 4, 1957. The whole world saw and heard this flight. The surprise led to unpredictable forces of international effect. The first machine created by man overcame the force of gravity and went into space. The creation of the R-7 rocket system took place.

For the launch of the first satellite, the Lenin Prize was awarded to Chief Designer V. Glushko and chief of fire tests laboratory V. Shabranskiy, with the title of Hero of Socialist Labor to Deputy Chief Designer V. Vitka and V. Kurbatov, assembly worker N. Vasilyev. Many employees were awarded orders and medals.

Improvement of the RD-107 and RD-108 engines, increasing their reliability, have continued. Many specialists of our company had to work sometimes 10–12 hours a day. As a result of a large number of ground development tests of the engines there was such a high reliability of engines accounting and flight tests that is was confirmed that it was possible to trust them to launch and deliver into space the first man.

For ensuring Yuri Gagarin's flight into space, our company OKB-456 was awarded by Lenin order, Chief Designer V. Glushko again was awarded by title of Hero of Socialist Labor, this title was awarded workers V. Zinoviev, M. Ilyushin, test foreman N. Shmagin, head of design department S. Agafonov, head of fire tests laboratory V. Shabranskiy, deputy chief designer V. Lavrenets-Semenyuk, and plant director Y. Soloviev.

The successful flight of Yuri Gagarin opened an era of space travel—an era of space exploration. Since the first launch, all cosmonauts and astronauts, launched from Baikonur cosmodrome, have flown from the surface of the Earth via RD-107 and RD-108 engines and their modifications. The same is true for the most part for unmanned spacecraft and satellites.

Since 1958 specialists from NPO Energomash and its Privolshskiy filial have continuously conducted supervision of serial production of the RD-107 and RD-108 engines, manufactured in Samara at plant #224 (later JSC "Motorostroitel," now JSC "Kuznetsov"). The NPO Energomash staff participated in all efforts regarding upgraded engines and new modifications.

So, since 1960, the challenge was to create new engines based on RD-107 (8D74) and RD-108 (8D75) engines. The 8D74K and 8D75K engines became the first modifications of basic RD-107 and RD-108 engines. Their differences were as follows: the 8D74K engine to reduce pre-launch flowrates has reduced the number of intermediate modes. The launch was carried out through two intermediate modes instead of three, and shut down via first intermediate mode. The 8D75K engine had increased operation time in final mode. These engines were installed on 8K78 LV. Furthermore, the 8D74K engine was assigned an 8D728 index.

To increase the payload, it was proposed to increase the 8D75K engine thrust by forcing its combustion chamber pressure up 5 percent, resulting in the increase of ground specific impulse of 2.9 seconds. The engine was developed in two versions: 8D727—forced up by 5 percent at shut down without final mode; 8D727K—forced up by 5 percent at shut down through final mode.

In 1968, development of the 11D511 and 11D512 engines began based on 8D727 and 8D728 engines. Structural differences were as follows: units of the control system of the engine were improved; range of operation of throttle of fine tuning was expanded; chamber with a large margin of stability was used for 11D512 engines.

In 1979, development of the 11D511PF engine began based on the 11D511 engine. The new version of engine used synthetic fuel—"sintin" instead of T-1 kerosene. Design features included the following: increased pressure in the chamber, spiral ribs of cooling ducts of the chambers, and delay in closing of the fuel valve at engine shut down.

In the modern version of the RD-107 and RD-108 based engines—14D21 and 14D22 engines the following design activities were implemented: new mixing head with a single-component injector, similar to the mixing head of the earlier developed RD-111 engine; anti-pulsation partitions from injectors of oxidizer and fuel protruding by 30 mm in direction of firing space; spiral ribs of the cooling duct in most heat-stressed areas of the chamber. Improvement of the mixing process resulted in an increase in vacuum specific impulse for the 14D21 engine of 4.6 sec. and for 14D22 engine of 6.2 sec. Flight tests of engines with an upgraded system of mixing in the chambers were completed in 2002.

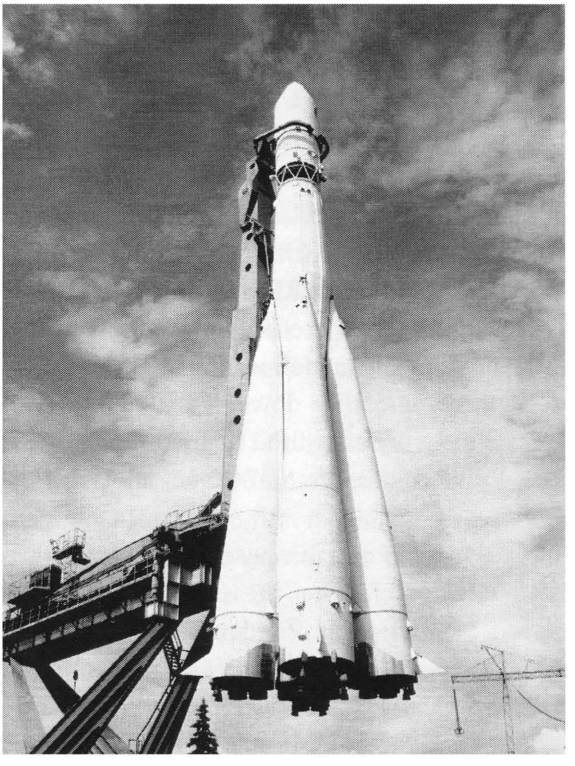

Figure 6–4: Launch vehicle on display at the VDNKh exhibition, Moscow. (Sergei Arssenev photograph).

For the same engines, a system of chemical ignition of propellant components in the chambers was tested in 1999–2002, however, despite obvious advantages, because of additional mass of 200 kg for LV, such advanced modification with chemical ignition is not implemented for the present time. It should be noted that the RD-107 and RD-108 engines are shining examples of outstanding achievements of our country in the field of rocket and space technology. This has been repeatedly demonstrated at international and domestic exhibitions since the middle of the 1960s of the twentieth century up to now: Expo-66, Canada, 1966; International aerospace salon, Le Bourget (France), 1967; exhibition in Budapest (Hungary), etc. An RD-107 engine for a long time was shown at the exhibition of achievements of national economy of USSR (VDNKh) in Moscow. A new exhibition—"Cosmonauts"—was opened in September at the Science Museum in London (United Kingdom) and an RD-108 engine is one of most important exhibits there.

The high reliability of the R-7 rocket, confirmed by flight statistics, allowed to provide extended operation that became a record for rocket technology—58 years. The quantity of manufactured engines has become truly "astronomical": with the number of rocket launches to date (7.09.15)—more than 1,900 [1,846 (for Samara serial production) plus about 100 (for Podlipki (OKB-1) initial production)], the number of flight engines is over 9,500, the number of manufactured engines is about 12,000. No other engines in the world have such prolific statistics.