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History of Liquid-Propellant Rocket Engines in Russia, Formerly the Soviet Union

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I. Introduction

THE history of liquid propellant rocket engines (LPREs) in the former Soviet Union is remarkable because they have developed a larger variety and a larger number of LPREs than any other nation and the number of their LPREs that have been flown is considerably larger than that of any other country. When the Soviet Union split into several countries in 1990, the work was continued, and almost all of the LPRE development organizations, manufacturing plants, and test facilities ended up in Russia. Only a couple are located now in the Ukraine, but they seem to work well with the Russian establishments. The major progress in the technology of LPREs and, thus, most of the key historical events took place when the government of the Union of Soviet Socialist Republics (USSR) ran the country.

There is no single LPRE concept or type, but rather several that are related. All of them have one or more thrust chambers.[1,2] As in other countries, there are significant differences between large (high-thrust) and small (low-thrust) LPREs, between engines using cryogenic or storable propellants, monopropellants or bipropellants, with a single start or with multiple restarts during flight, those with pumps or gas pressure expulsion of propellants in their feed systems, and with a single flight or reusable for multiple flights. The history of all of these types is discussed.

Design bureaus, government laboratories, and vehicles will be identified by their names and in some cases also by the names of a few of their leading people. Unfortunately we cannot list all of the important Russian organizations or people who were leaders or strong voices in these LPRE teams. Soviet LPREs have usually more than one alphanumeric designation for a LPRE, such as those from the engine design bureau, the government, or the vehicle designer. In this paper, an LPRE will be identified by the vehicle application and/or the developer's designator.

In this paper a *successful LPRE* is defined to have been put into serial production and/or to have flown satisfactorily more than once. There have been many experimental and prototype LPREs and engine components that were conceived, designed, built, and tested, but for various reasons were never flown or produced in quantity, and most fell by the wayside. This article will concentrate on some of the successful Russian LPREs. However, a few other developments that may not fit this definition of success, but have interesting technology or some historic significance, will also be discussed.

It is not the purpose of this historical paper to present detailed information on specific LPREs or to include all of the Russian LPREs. There are far too many of them. Only a few have been selected, and for each of these only very limited data and/or a brief description is given. Some of the LPRE have never been reported in the literature, some have been briefly mentioned in publications with limited distribution and are unknown outside of Russia. Therefore, these cannot be included in any U.S. paper. For more detailed parameters and for other engines, the reader is referred to the references and to a future book on the history of LPREs by the author expected to be published by the AIAA late in 2004. Although some of the flight vehicles driven by a LPRE (airplanes, missiles, space launch vehicles, spacecraft, etc.) are mentioned here briefly by name or identification number, the emphasis in this work is on the rocket engines. This paper will not cover Soviet solid propellant rocket motors, nuclear or electrical propulsion, turbojets, and combination rocket–airbreathing engines.

II. K. E. Tsiolkowsky and the Earliest LPRE Concepts

The first serious technical mention of a LPRE in world history has been credited to the Russian Konstantin Eduardovich Tsiolkowsky (1857–1935).[3–5] He was a self-made man, had a serious hearing impairment, read avidly, and studied by himself. Most of his life, he taught high school mathematics and physics in Kaluga, a provincial town. In his spare time he diligently pursued his analysis, his writing, and his research.

He had three main technical interests. He investigated airborne dirigibles with a metal skin and heated gas, but his ideas were never really supported. He studied metal airplanes and aerodynamics; he built an "aerodynamic pipe" or wind tunnel, the first in Russia, and with it, he determined the drag coefficients for a variety of simple aerodynamic shapes. His avocation and main interest, however, was spaceflight, and he wanted to do it with LPREs.

He started his deliberations about spaceflight and rocket vehicles in about 1883. After trying for several years to publish his

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article "Exploitation of Cosmic Expanse via Reactive Equipment" (also translated as "Investigating Space with Reaction Devices"), he finally succeeded in 1903, when an obscure magazine in St. Petersburg accepted it. Because the article was long, it had to be published in two installments. Because the magazine that printed the first part in 1903 went out of business, the second part was published in a revised form only in 1911 in another magazine. This historic literary work was published again (in Russian) in 1912, 1914, and in an expanded version in 1926.

In these papers, he described the use of rocket propelled vehicles for investigating the upper layers of the atmosphere and, in the future, for interplanetary flight. He was the first to show the equation for the Earth escape velocity, and he was the first to develop the equation of rocket motion in a flight with decreasing mass, which has also been called the Tsiolkowsky equation. It defines the theoretical velocity achieved by a flying vehicle that has been accelerated by rocket propulsion, while its mass decreases by the propellant consumed. In its idealized simple form, it gives the flight velocity in a gravity-free space vacuum.

He also wrote about an artificial spaceship like the moon, but brought arbitrarily close to our planet to a height just beyond the atmosphere. Today it is called a satellite. He mentioned two-staged vehicles, weightlessness in space, and rudders for steering. He superficially discussed interplanetary platforms as in-between stations en route to the moon or the planets, and he suggested gyroscopic stabilization.

Tsiolkowsky analyzed the energy required for spaceflight and analyzed the energy available from a number of different propellants. He concluded that liquid bipropellants had more energy than solid propellants and, therefore, were preferable for spaceflight. He made only a few vague conceptual sketches of a "liquid propellant reaction device" and gave rather general verbal descriptions. He wrote about a pumped propellant feed system and the expansion and acceleration of the gases in the nozzle, and he believed that good mixing was necessary for high combustion efficiency.

In his conceptual sketches the LPREs had a very small combustion chamber and a very long, trumpet-shaped exhaust nozzle with a small conical angle. Figure 1 shows the nozzle exit section is trumpet shaped, which would be inefficient, and extended almost the full length of the vehicle. His sketch indicated piston pumps, but their power source or cyle are not explained. He also stated that the chamber walls needed to be cooled, and he suggested the fuel flow as a coolant. His propellant tanks were odd shaped, structurally heavy, and not of the right volume proportions. In spite of the inadequate detail, he was the first to write seriously about his concepts of a LPRE. He did not build nor test a LPRE. Robert H. Goddard of Massachusetts built the first thrust chamber (TC) in the early 1920s and flew the first rocket vehicle propelled by a LPRE in 1926.

Tsiolkowsky studied the heat release and suggested several liquid propellant combinations, an amazing accomplishment for a visionary who never had a good technical education or any direct personal experience with propellants. In his analyses, liquid oxygen was the only oxidizer, but he had proposed several fuels, namely, alcohol, some hydrocarbons, including methane, and liquid hydrogen. He selected liquid hydrogen and liquid oxygen as the best combination for spaceflight because they were more energetic, and this conclusion is still valid today.

Tsiolkowsky received recognition for his pioneering studies only when he was in his 60s and 70s. With it came a more adequate support for his living. In the late 1920s and 1930s he became well known in the Soviet Union and famous as a world-renowned space scientist. Many of his concepts, notes, propulsion ideas, or theories were published 5–20 years after his death.

III. Amateur Societies

In 1924 the world's first amateur rocket society was founded in the Soviet Union and was called the All-Union Society for the Study of Interplanetary Travel".[6] Similar amateur societies were established in Germany (1927), the United States (1930), Great Britain (1933), and other countries. These amateur societies were evidence of the great popular interest that developed in rocketry and spaceflight. This Soviet amateur organization attracted people like Konstantin Tsiolkowsky and Frederikh Tsander and soon had 200 members and over 1000 a few years later. Similar groups were set up in other Soviet cities. The group in Kiev organized an exhibition and lectures on spaceflight and rocketry in 1925. The Soviet government at that time encouraged scientific debate and discussion, and they supported and controlled these groups from Moscow.

This society concentrated on spaceflight, but some of their papers, exhibits, and discussions related to LPREs. Visits and lectures by foreign experts were permitted. The acceptance by the technical community was enthusiastic. These groups contributed greatly not only to popularize the subject (with a lot of free publicity), but also to attract and educate people, who later developed and built rockets. It also caught the interest of key Soviet government officials, who later funded rocket research. The Soviet Union was unique in this respect, for no other country at that time had intellectual technical debate on spaceflight or rocketry. Beginning in about 1930, after Joseph Stalin had come into power, this freedom of technical discussion was no longer allowed, and these Russian amateur societies disappeared.

IV. Propellants and Combustion Stability

These two areas are important in the technology for LPREs, and although they are again mentioned later in the text with specific engines, they are briefly summarized in a simplified way here.[1–3,7–9] A variety of liquid propellants were investigated in the Soviet Union. In May 1946, the government set up a new research organization in Leningrad called State Institute for Applied Chemistry to explore, develop, or synthesize propellants for the Soviet missile and space program. The early LPRE programs (1932–1940) seem to focus on liquid oxygen (LOX) with kerosene (for good performance) and nitric acid with a hydrocarbon fuel (for storability), but other

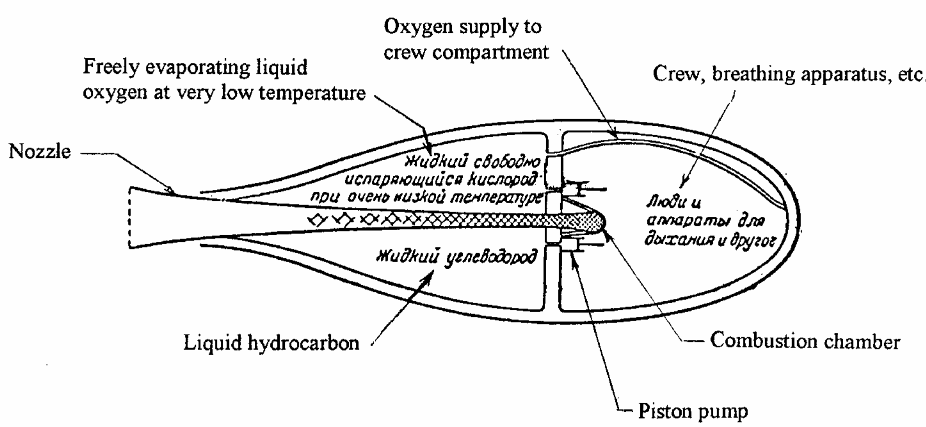


Fig. 1 One of Tsiolkowski's imaginative sketches of his 1903 visualization of a future spaceship (adapted from Ref. 3).

propellant combination were also tested, for example, turpentine, gasoline, or certain monopropellants. When the Soviets acquired and copied the German V-2 technology, they built missiles with the V-2 propellants, namely, LOX/alcohol beginning in 1946. In the 1950s, they switched back to LOX/kerosene for large engines because this gave better performance. Storable propellants for large engines were used commencing around 1958 because they allowed missiles to be ready for launch at any time. Initially they used nitric acid (usually with N_2O_4 additive), but they experienced major corrosion difficulties. In the 1960s they settled on nitrogen tetroxide (NTO) and unsymmetrical dimethyl hydrazine (UDMH) as being the most practical storable propellant combination. It had predictable properties, was storable for long periods, was essentially noncorrosive, and still gave good performance. It has been used ever since as the major propellant combination for Soviet military applications, space launch vehicle (SLV) upper stages, attitude control engines, spacecraft maneuver engines, and satellite propulsion. The United States seemed to have focused on NTO/monomethyl hydrazine (MMH) and a mix of UDMH and hydrazine for these same applications.

The Soviets pursued experimental programs with high energy propellants for about 25 years. Starting in the 1960s, the Soviets developed and built at least three and perhaps as many as six LOX/liquid hydrogen (LH_2) LPREs (by three different design bureaus) for high-performance space missions, but only one has successfully flown beginning in 1987 (RD-0120 in Energiya Space Launcher), and none has flown in Russia since 1996. At the time of this writing there did not seem to be an active flight program with these cryogenic propellants. They also developed LOX/methane engines, but they apparently did not fly. Two other high-energy propellant combinations, namely, liquid fluorine with ammonia and concentrated hydrogen peroxide with pentaborane, were chosen for serious engine developments, but these engines were abandoned.

The Soviets synthesized a novel type of kerosene called sintin, which gave a little more performance (2–4%) than the ordinary kerosene used with LPREs. They also used subcooled LOX, which was slightly denser (improves vehicle mass ratio) and colder than LOX stored at atmospheric pressure. It has a higher capacity to absorb heat and is easier to pump (lower vapor pressure and less likely to cavitate) than ordinary LOX, which has a temperature close to its boiling point. With these two modified propellants, they achieved a better performance than ordinary LOX/kerosene (typically 20 s more vacuum specific impulse), and this provided a substantial extra margin (without any real engine change). Sintin and subcooled LOX were used in engines of selected upper stages for certain deep space missions, such as in the Proton SLV. Although one source mentioned that this propellant combination was used also on large booster rocket engines, the author has not been able to verify this.

It is well known that high-frequency combustion vibrations at 1000–20,000 cps can destroy a TC in much less than 1 s by structural failure or burn out. Therefore, the occurrence of this vibration must be completely eliminated during engine development.[2] These gas oscillations were first encountered by the Soviets with large TCs in the late 1940s and early 1950s and have plagued the development of several of their large engines since that time.[10,11] These gas oscillations usually occurred either during steady-state operation or during the thrust transient at the start, but occasionally also during shutdown or thrust changes. Investigations of these phenomena were given a high priority, were worked on intensively by many of the design bureaus in the 1950s–1970s, and included research and development (R&D) efforts at the Keldysh Research Institute, other institutes, and some universities.

As a result of these investigations the Soviets, just as the other countries, obtained a better understanding. The high-frequency combustion vibrations were intimately associated with the combustion processes and their energy release mechanisms. Pressure waves could resonate at high amplitudes in an axial, radial, or tangential mode. Several remedies have been effective in eliminating the sudden occurrence of high-frequency destructive vibrations. They included these: 1) Early solutions were to change the resonant frequencies by changing chamber geometry (diameter or length). Some types of vibrations were more likely to happen with larger chamber diameters. During an early LPRE development in about 1946, when chief designer Alexander Isayev went from a single large TC to four smaller TCs of the same total thrust, he found it easier to cure a troublesome vibration. This is in part a reason for using four TCs in several LPREs. 2) Instabilities occurred more readily with certain propellant combinations, and a change of propellant has at times been effective. For example LOX/hydrocarbon is more likely to have combustion vibrations than LOX/alcohol. The early OR-2 engine was switched from gasoline to alcohol. 3) They used cooled metal baffles as early as 1949 (initially in the shape of a cross) near the injector to eliminate transverse gas vibrations. This was first achieved early in one of Isayev's TCs. 4) Vibrations occurred at certain regions of the chamber pressure vs mixture ratio spectrum, often during thrust buildup or throttling and occasionally during shutdown or thrust changes. A change in start sequence, transient flow, or local mixture ratio was sometimes effective. 5) Certain injection elements, patterns, or orifices were more stable, and minor changes in their geometry sometimes had a large influence. The Soviets had a long history of using spray nozzle elements in their injectors, and they learned how to change the detail dimensions of these elements to control the flow, swirl, and the location of the impingement of the two propellants and, thus, the axial location of the maximum energy release. In some cases, it was was possible to eliminate instability by making certain changes in the geometry or the flow of individual spray elements or in the distribution of spray elements over the face of the injector, flow densities, or local mixture ratios over the surface of the injector. This resulted in some complex injection patterns described later. 6) If gas bubbles enter the combustion chamber, they can often trigger instability. Therefore, precautions were taken to drain properly or eliminate gas bubbles in the propellant feed lines and to prevent tank pressurizing gas from entering the tank outlet during maneuvering flight operations. 7) Theory now permits designers to calculate estimated values of the likely gas resonance and harmonic frequencies in all three modes (axial, radial, or tangential). This allows the designers to design the LPRE, its structure, and key components so that their natural resonance frequencies will not coincide with those of the combustion gas vibrations, thus, avoiding uncontrolled vibration amplifications and potential overstressing of parts. 8) There was one other remedy that worked well, and as far as this author knows, was not practiced outside the Soviet Union. It is temporary baffles in the chamber; they are made of feltlike material that is porous and combustible. They work only during the start transient and the first few seconds of burning, before the baffles are consumed.

One or more of these various remedies were successful in eliminating combustion instabilities during development of each new Soviet LPRE. None of the remedies listed were 100% effective for different TC designs, transients, sizes, propellants, chamber pressures, or mixture ratios. It still is not always clear which of these approaches will be most effective and simplest for a particular TC that has experienced incidents of combustion instability. The Soviets did not appear to use resonance cavities as a remedy, which were very effective in the United States and other countries.

V. Early History, 1929–1945

The early amateur effort in the Soviet Union and the visions of Tsiolkowsky were the preludes to steady and continuing government-supported efforts in LPRE R&D. In 1919, Nicolai I. Tikhomirov, a spaceflight enthusiast, wrote a letter to Lenin, the Communist leader of the country, asking for a government grant to do serious research on solid and liquid propellant rocket propulsion.[4] This request was reviewed by the Soviet Military and other government bureaus and was granted two years later. Originally this government group was founded in Moscow in 1921 as Tikhomirov's Jet Propulsion Laboratory and later it was moved to Leningrad (now known again as St. Petersburg). Initially this group concentrated on theory and solid propellant rockets.

Early LPRE efforts were well documented.[4,5,8,9,12–15] In June 1928, Tikhomirov's laboratory was reorganized and called the Gas Dynamics Laboratory (GDL). It was in 1929 that work on LPREs was begun. In 1931 Valentin Petrovich Glushko became the leader

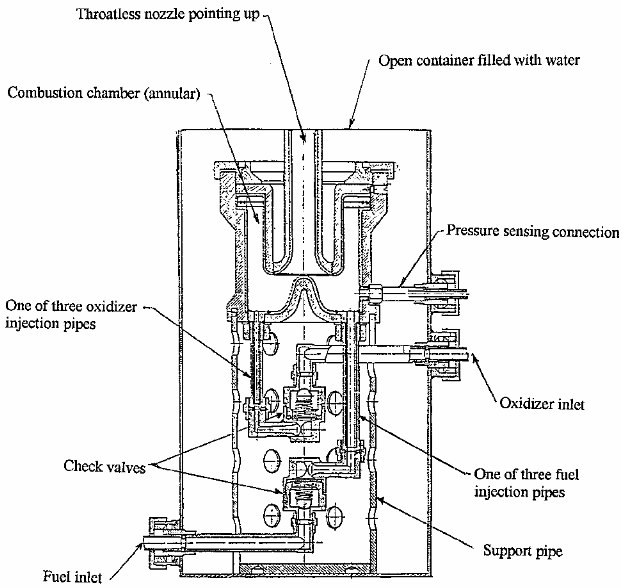


Fig. 2 General view and cross section of the first Soviet thrust chamber ORM-1 fired in 1931 (courtesy Energomash).

of LPRE effort within this GDL. He and his group are credited with the development of several early Russian thrust chambers and some LPREs and with proposing the concept of hypergolic ignition. Beginning in 1946, Glushko headed the Soviet effort to build and test copies of the German V-2 LPRE, and he played a leading role in the subsequent development of large LPREs, which were used to propel most of the large Soviet missiles and space launch vehicles.[14] Glushko is identified with many advances of LPREs as explained in Sec. VII.A.

The first Soviet thrust chamber, Opytni Raketnyi Motor number 1 (ORM-1) was designed by Glushko's group at GDL and was test fired in 1931. Figure 2 shows an annular cylindrical chamber; it was internally plated with copper (supposedly for good conduction of heat) and equipped with three reentrant interchangeable steel nozzles (each with a different throat diameter), also copper plated. A thin layer of gold was plated over the copper to minimize corrosion. The propellants were toluene and oxides of nitrogen. The tests were with a cutoff nozzle (no diverging nozzle exit section) pointing straight up. Ignition was by alcohol-soaked wadding previously placed into the chamber and ignited by a small fuse. The TC could run for a few seconds without burn out. Between 1933 and 1937, the group designed and tested many ORM configurations. By 1934, they had a TC that could run for more than a minute with a propellant cooled nozzle and an uncooled chamber/injection assembly. In subsequent models, ignition was obtained by a small solid propellant (gun powder) charge, which was ignited by an electric squib, and later by injecting a hypergolic (self-igniting) start fuel. A more advanced version, the ORM-50, had a regenerative cooling jacket only around the nozzle, but an uncooled chamber with side injection (two oxidizer and two fuel spray heads) and some film cooling. The hypergolic startup propellant with nitric acid was a mixture of phosphorus, carbon sulphite and turpentine.

The idea of a curved nozzle exit contour was supposedly mentioned in a letter by V. P. Glushko to K. E. Tsiolkowsky in 1930. In the 1930s and 1940s, the GDL undertook some experimental work comparing different nozzle lengths, exit cone half-angles, and exit contours (bell shape) using a pendulum balance with two opposed nozzles. With this technique, they optimized the cone half-angle. Later tests were made with bell-shaped contours, which reduced the divergence loss and gave slightly higher performance than a cone of equal length. Some of the small ORM TCs tested at the GDL had curved nozzle exits, but most used conical exit sections. Conical exit sections (12–18 deg) were used on many of the early large TCs (1946–1950), and curved exit contours appeared in large TCs in 1951–1953. The United States began using bell-shaped nozzle exits in 1957–1960 (Energomash private communication on pendulum).

In August 1931, the Moscow Gruppa Isutcheniya Reactivnovo Dvisheniya [Group for Investigation of Reactive Engines (GIRD)] was set up with government support.[4,8,9,13,15] Several former members of the Moscow amateur society joined this Moscow GIRD. Initially it had groups for LPREs, vehicles propelled by LPREs, ramjets, and jet engines. Other GIRD groups were also set up and controlled from Moscow, such as those in Gorkiy, Kiev, Khrakov, Tbilisi, and Rostov. In 1932 Sergei Pavlovich Korolev (1907–1966), an engineer and pilot, became the leader of the Moscow GIRD. He personally designed unmanned aircraft and rocket vehicles at GIRD and occasionally helped on LPREs. Korolev later became the top man in all of the Soviet long-range missiles and spaceflight vehicle efforts, and he was made a member of the Soviet Academy of Sciences.[16] His key job as the leader of the Soviet ballistic missile and space program and his membership in the Academy were kept secret; only on the day after his death in 1966 did his role become known.

Fridrikh A. Tsander, a disciple of Tsiolkowsky and one of the early Russian visionaries and pioneers in rocketry, became the department head at Moscow GIRD for the development of LPREs. Tsander had already worked on the analysis of LPRE for several years and had published "Flights to Other Planets" which made him popular. (see Refs. 5 and 17). This department worked independently from the GDL in Leningrad. The GIRD group test fired its first engine in 1932, known as OR-1, running on compressed air and gasoline at an intended thrust of 12 lbf. Because it used air, some people considered it to be more like a jet engine than a rocket engine. It used a spark plug for ignition. One source reported that Tsander ran a version called OR as early as 1931, which would have been the first Soviet TC firing.

The next model, OR-2, shown in Fig. 3, was a relatively complex LPRE and was intended to be installed in a glider.[8,15] Design thrust was 50 kg f, and propellants were LOX and gasoline. It evaporated liquid nitrogen for gas pressurization of the propellant tanks and used forced-flow water cooling of a tank built around the nozzle. It had heat exchangers for evaporating the LOX and the liquid nitrogen with the water, which had been heated by heat transfer from the nozzle. There was a closed water circuit with an electrically driven pump. During the early tests of the OR-2 engine in March 1933, there were several explosions and also problems with unstable combustion. They learned lessons from these failures and made improvements to this engine.

After Tsander's untimely death in 1933, his group continued the work. More than 100 different and more advanced engines were designed or developed (1932–1937) in Moscow and Leningrad, some with different propellants (but the Moscow people used mostly LOX and kerosene or gasoline and the Leningrad people used mostly storable propellants). They tried different injector spray elements, alternate injector locations, different internal coatings, alternate igniters, or different wall or injector materials. By the beginning of 1934, the Soviets had developed reliable pyrotechnic igniters and later (1937) hypergolic ignition (tested at chamber pressures up to 25 atm) and obtained specific impulses of 175–210 s. Thrust levels were increased to 3000 lb. They experimented with a ceramic-lined TC using aluminum oxide for the chamber and a magnesium oxide formulation in the nozzle, but it was heavy, cracked at times, and not reliable. An improved ceramic version, called 12K, was used for propelling flight-test vehicles in 1936 and 1937; one was used with a winged vehicle.

The GIRD department under Tikhonravov in Moscow and the GDL in Leningrad designed and developed rocket propelled vehicles with LPREs. The Soviets flight tested several of their newly developed LPREs to evaluate the effects of flight accelerations and the atmosphere environment. Vertically ascending test vehicles were designed and flown. The first flight of the new Moscow GIRD took place in August 1933. This experimental rocket propelled vehicle, GIRD 09, was 7 ft 10 in. tall, had a pressurized gas feed system, had 42 lb of liquid propellant, and ran with a resin-modified gasoline fuel and LOX. It ran 18 s, reached an estimated height of 1300 ft; its combustion chamber had burned through and it fell back to Earth.

In 1932 the informal Moscow GIRD group and the GDL in Leningrad were merged into a single government research and

Table 1 ORM-65 TC

Characteristic	Value
Propellants	Nitric acid and kerosene
Thrust	155 kgf (341 lbf) rated, 50–175 kgf possible
Chamber pressure, nominal	22 atm (323 psia)
Specific impulse, see level	210 s
Duration	38 s typical, longest test run 230 s
Propellant tank pressure	35 atm (514 psi)
Cooling of chamber and nozzle	With nitric acid as regenerative coolant Film cooled at head end only Jacket had spiral passages in chamber and nozzle
Outside temperature of head	300–400°C (391–751°F) during operation
Weight, total	14.26 kg
Length/maximum diameter	465 mm/175 mm
Inside chamber diameter	102 mm

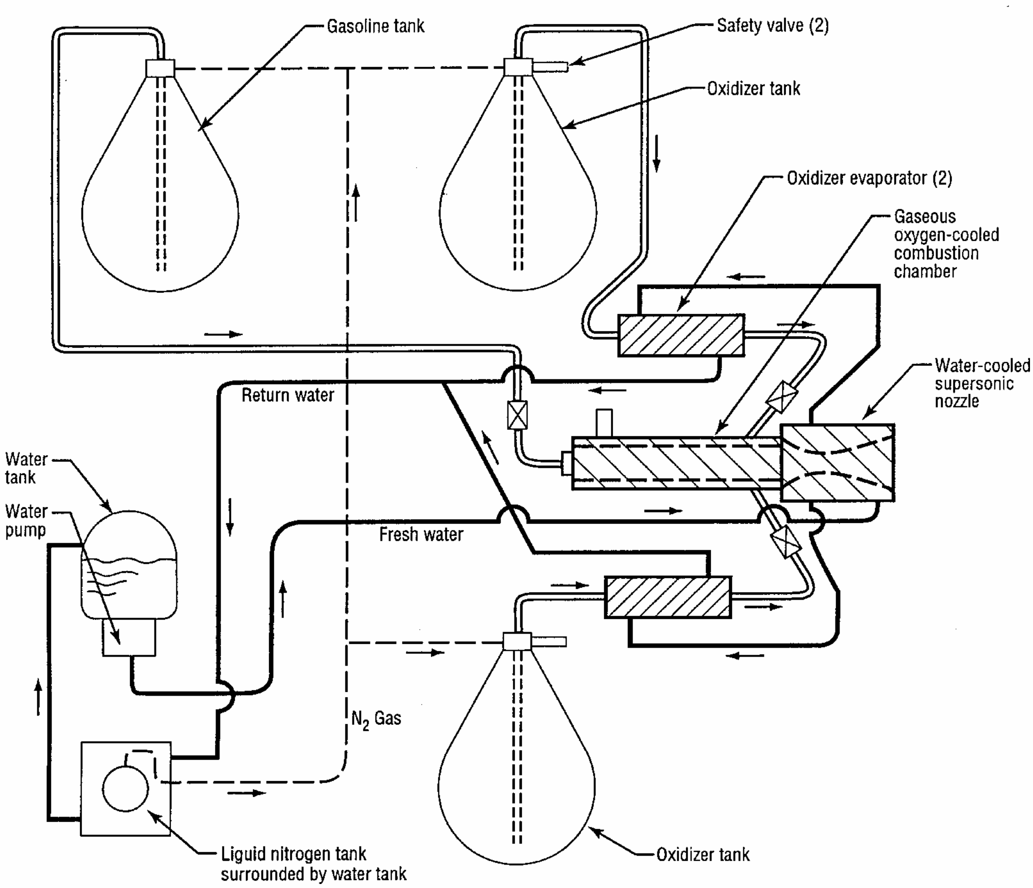


Fig. 3 Simplified flow diagram of the OR-2 originally designed by F. Tsander (adapted from Ref. 8).

development organization. It was known as the Reaktirnyi Nauchno Issledovatel'kii Institute or Reaction Propulsion Research Institute (RNII). Its LPRE section investigated and tested many different ideas, such as different TC configurations, nozzles, injector locations, and chamber volumes. The early TCs generally had uncooled chamber walls, but the nozzles were usually regeneratively cooled. The injection was mostly by spray nozzle inserts at the midlength of the chamber. Many ideas were not successful, such as air cooling of TCs or some ceramic coatings. RNII built the first heavy-walled firing test stands with remote control. They designed LPREs for experimental sounding rockets, an experimental aerial torpedo, military missiles, and experimental rocket airplanes.

In November 1933, the Moscow team of RNII flew the RP-1 unmanned glider with an improved version of the OR-2 LPRE originally designed by Tsander. In March of 1934, the same engine propelled yet another pilotless rocket aircraft. In May 1936, a winged rocket propelled unmanned projectile, known as Model 216 was launched from inclined rails for the first time. It had a modified OR-2 LPRE using alcohol and LOX delivering 220-lb thrust at take off. A later version Model 212 flew twice in 1939, but failed to achieve the predicted flightpath.

The Leningrad team of RNII developed a series of LPRE designated ORM-3–ORM-66 using various propellants, mostly storable propellants with nitric acid or nitrogen tetroxide as oxidizers. Beginning with ORM-34, all TC nozzles were cooled by one of the propellants flowing through some type of cooling jacket around the nozzle section. Several of these engines were selected and modified for application to military aircraft or missiles. The ORM-65 engine, first tested in 1936, was one of the more successful pressure fed LPREs with storable propellants.[4,8,13] Technical data is given in Table 1 and its TC is shown in Fig. 4.

There were three steel parts in the TC, the head, the chamber with its nozzle, and the outer housing, and they were threaded together with asbestos packings for sealing the joints. The space between the

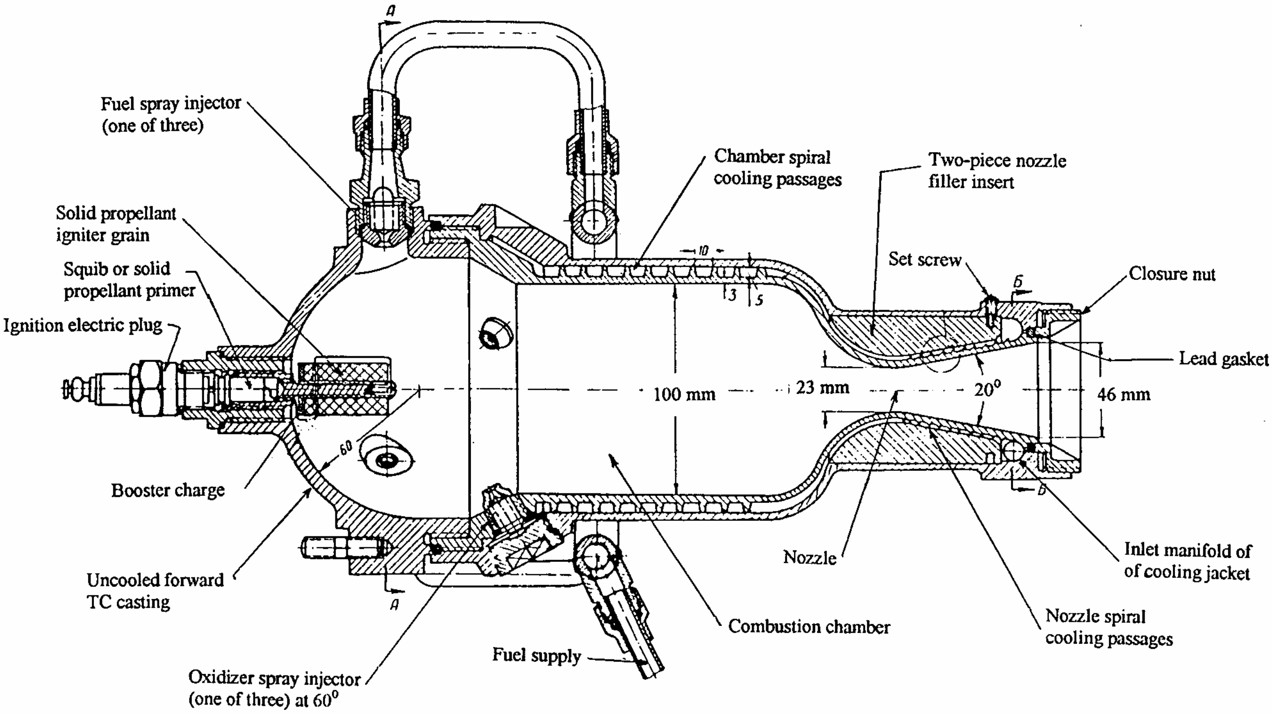


Fig. 4 Historical ORM-65 thrust chamber[4,8] flown between 1936 and 1939 (courtesy Energomash).

nozzle wall and the housing was filled with a split aluminum insert, pinned and fastened with a locking screw. The thermal expansion of the inner wall was compensated by a lead ring, which was tightened by a threaded annular nut. During operation, the lead extruded into a gap. The nut had to be tightened after every run. The injector had three inclined spray heads of fuel injected at right angles to the axis and three spray heads for nitric acid inclined at 60 deg to the axis. The spray heads had swirl inserts (helical passages) and were sealed with aluminum packings. The nitric acid was heated as it flowed through the spiral channels of the cooling jacket before injection. The front end of the chamber did not have a cooling jacket. The electrical squib had a resistor that burned out when the circuit was closed, igniting the small gun powder charge inside the squib. The hot gases ignited the solid propellant grain, which in turn ignited the liquid propellants. The solid propellant was a mixture of nitrates with powdered metal fuel. This engine was put into production, run for many static test firings, 49 vertical launches, and for propelling an experimental aerial torpedo. It was also used for a tied-down rocket propelled experimental RP-318 military aircraft in 1937 and 1938. This TC became a model after which a series of other TCs were patterned, and it had many of the TC features commonly used thereafter.

The first gas generators (GG) were designed and ground tested at RNII between 1935 and 1937.[8] Three propellants were used: nitric acid, kerosene, and water. The water was the coolant of the GG chamber cooling jacket, and it also was injected as the diluting agent or gas cooling agent. As seen in Fig. 5, the GG had two chambers: one for the hot combustion (chamber cooled with water) and one for mixing and achieving a uniform composition and temperature. A few years later the water was replaced by a water–alcohol mixture, which had a lower freezing point. It was not until 1945 that a GG was ground tested with a turbopump (TP) in a engine, in part because up to that time they had a satisfactory feed system using gear pumps driven by piston engines as described later. Their first full TP-fed engine (with centrifugal pump impellers and a GG) was ground tested at RNII in 1945. Except for a poor photograph, no details were found on these early TPs.

Initially they had positive displacement pumps and gear pumps. Goddard in the United States also started out with such positive displacement pumps in 1924. The RD-1 engine, discussed in the next section, had gear pumps driven by a piston engine.

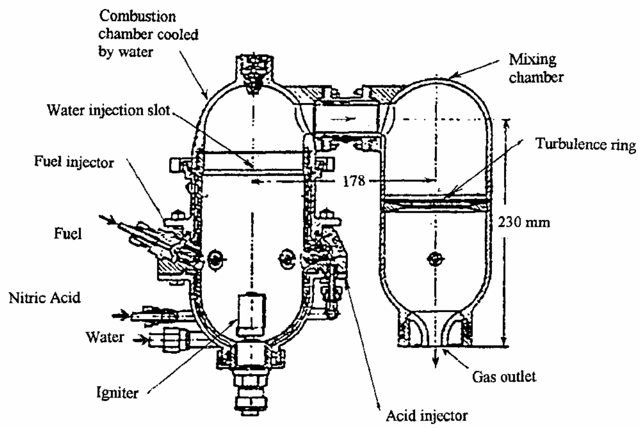


Fig. 5 First GG used three propellants and had two chambers.[8]

VI. LPREs for Piloted Aircraft, 1938–1957

In the late 1930s and the 1940s, there was a military need for increasing the rate of climb and the altitude speed of fighter aircraft to intercept bombers. LPREs were a potential solution and the Soviets built and flight tested about 15 such LPREs, which is a large number.[5,6,8,13,15,17]

The RDA-1-150 aircraft rocket engine was developed at RNII during 1938 and 1939 with nitric acid and kerosene propellants. It had dual regenerative cooling, that is, the kerosene cooled the nozzle at relatively high cooling velocities and the acid was circulated through spiral channels around the chamber inner wall. The injector had spray heads or spray nozzles, had internal cooling, and had a thermal protection on the inside. This first aircraft LPRE had clever features, novel at the time. Reportedly it had a dual-stage ignition and used an electric spark and had a reduced but controlled low initial propellant flow. The injector, chamber, and nozzle were separate subassemblies with a series of joints for thermal expansion in the outer wall. Supposedly the thrust could be varied from 80 to 150 kg (176 to 330 lbf) with the chamber pressure between 8 and 15 atm at a specific impulse of 150–198 s for a maximum duration of 200 s. It had a gas-pressurized feed system, which made it heavy. It was

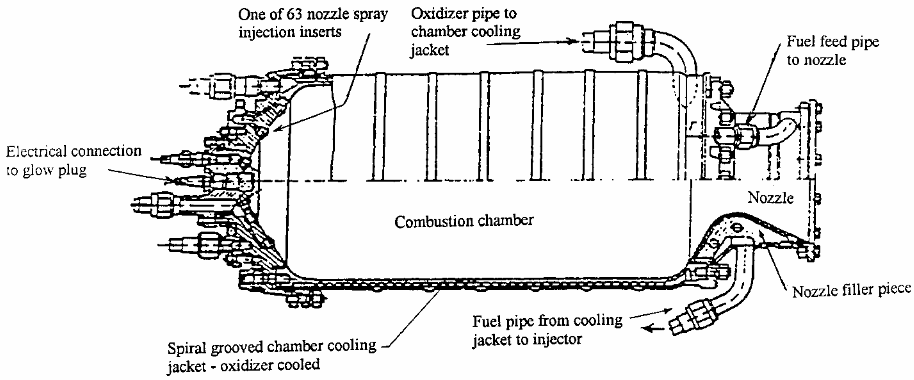


Fig. 6 One version of the thrust chamber assembly of the D-1-A-1100 engine,[8] which powered the first Soviet manned flight take-off in an BI-1 airplane in 1942.

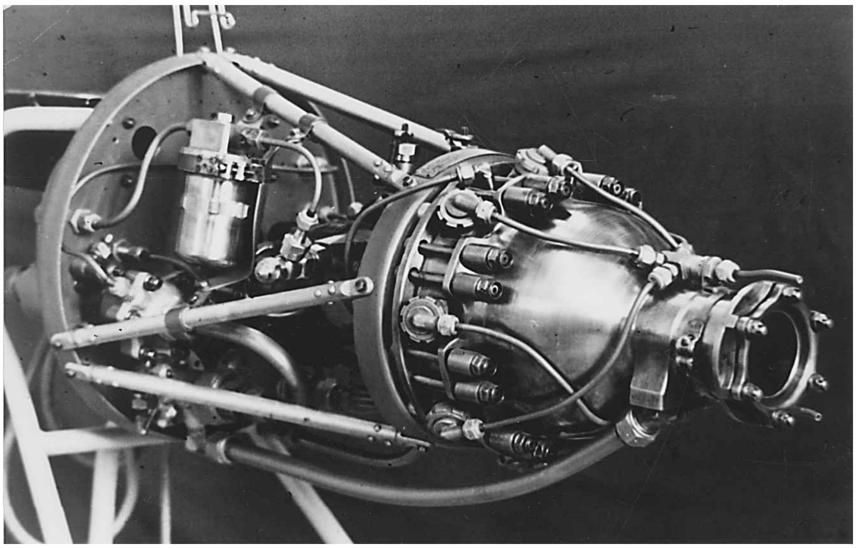


Fig. 7 RD-1 aircraft rocket engine's chamber and nozzle are cooled by oxidizer and ignition chamber is cooled by fuel (courtesy Energomash).

first flown as a power plant for the RP-318 aircraft on 28 February 1940. It was called a glider because it was towed to altitude by another aircraft. This was the first time in history that a pilot was propelled solely by an LPRE. It came a year or two before the Germans flew a rocket propelled aircraft (early version of Me 163) and several years before the United States accomplished a rocket powered glider flight. The flight tests with this engine did not give the desired results because the thrust was too low and the gas-pressure feed system was too heavy.

In 1941, the design of the historic D-1-A-1100 LPRE (credited to Leonid S. Dushkin) was started at RNII for a military aircraft superperformance and takeoff engine. It used nitric acid and kerosene as propellants, had a pressurized-gas feed system with heavy tanks, had a thrust that could be varied from 1100 down to 350 kg (2420 to 770 lbf), had a specific impulse of 203–156 s and could run up to 3 min uninterrupted.[8] One version of the TC of this historic LPRE is shown in Fig. 6. The nozzle was cooled by the fuel, and the chamber had a nitric acid cooling jacket, similar to some earlier TCs. By 1941, RNII had developed TCs with the injector spray elements at the forward end, which gave better performance and replaced injection elements at the middle of the chamber. This injector had a central glow plug igniter and 63 individual injection spray nozzles arranged in a five-ring circular pattern. The two main propellant valves were downstream of the cooling jackets. After some test firings in a tied down aircraft and some runway hops, the airplane was towed to altitude and released as a glider. Its first rocket powered takeoff and piloted flight took place on 15 May 1942, a key date in Soviet LPRE history. The aircraft was the BI-1 fighter and made mostly out of wood, and only seven aircraft were built. To prevent a reaction between the acid and the wood, the engine compartment was lined with stainless steel sheet. Flight testing continued periodically until 1945, when the end of the war stopped further work. The airplane and also the engine were never put into production.

The next set of aircraft LPREs were designed and developed during the early 1940s by Glushko's Design Bureau, which is also mentioned again later.[8,13] The RD-1 engine, shown in Fig. 7, used nitric acid and kerosene, had a sea level thrust of 300 kg (660 lb), and had a specific impulse of 200 s. The nitric acid supply pipe is at the bottom of Fig. 7. Ignition was with a spark plug and an initial flow of an ether–air mixture. The engine used gear pumps, and its flow diagram is shown in Fig. 8. There were several versions of the RD-1 engine. All had regenerative cooling and injectors with multiple inserts, through which propellants flowed and sprayed into the chamber. One model of this engine (RD-1 KhZ) was ignited by the injection of a slug of hypergolic propellant. In another version, the hypergolic igniter fluid was supplied through a rotating arm, which was placed through the nozzle into the chamber during start. The arm was then swung out of the way. These were the only flying LPREs where the propellants were pressurized by gear pumps, as seen in Fig. 9. The pumps were driven through a clutch by a jackshaft from the aircraft's piston engine. These positive displacement gear pumps assured operation at the intended mixture ratio. The gears of the acid pump had to have a generous clearance, so that there would not be a direct contact of mashing gears, which would cause local heat generation and also potentially a strong chemical reaction between the acid and the metal. By 1944, a special lubricant

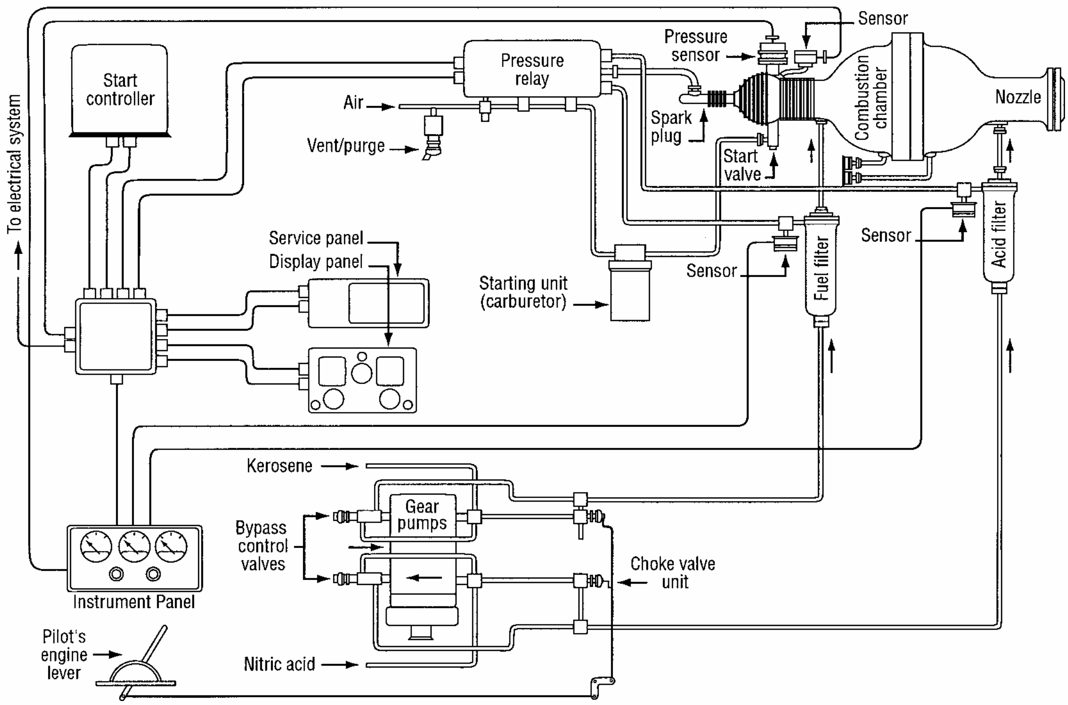


Fig. 8 Simplified schematic flow diagram of the RD-1 (1942)[8] (courtesy Energomash).

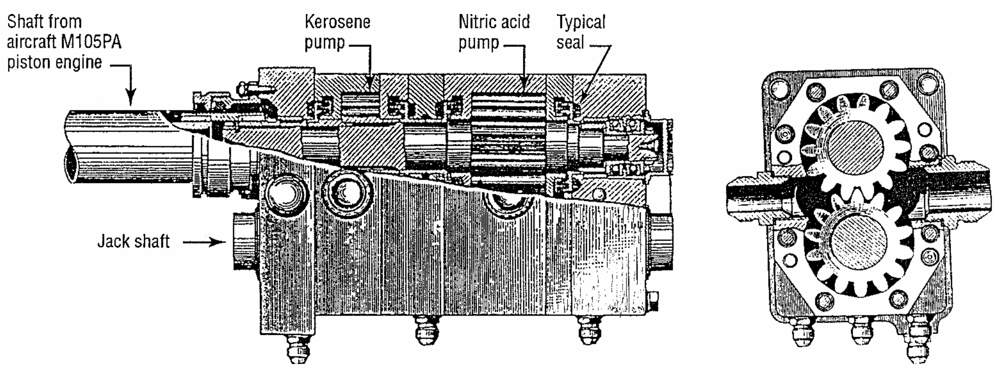


Fig. 9 Section of the gear pumps of the RD-1 (courtesy Energomash).

called nitro-oil was developed, which did not react with the acid, and it was used in valve seals, TP seals, and in pump bearings in several of these aircraft LPREs. Two models, the RD-1 and the RD-1 KhZ, were put into production specifically for investigating superperformance or assisted takeoff in flight tests of at least six different military aircraft.

The RD-2 used the same propellants and similar gear pumps as the RD-1, but had variable thrust initially between 200 and 600 kg and used chemical ignition (hypergolic initial fuel). Model RD-2M had a single TC with a thrust range between 350 and 1400 kg, and Model RD-2M3V had two TCs with an overall thrust range between 100 and 1500 kg. This experimental engine also was flight tested. As far as the author can recall, this 15 to 1 throttling range has not been equaled in other aircraft LPREs. The experimental RD-3 had three TCs, a variable thrust between 100 and 900 kg, gear pumps, and also used nitric acid and kerosene, and was developed between 1944 and 1945, but flight records could not be found.

The initial RD-1 TC had a separate small ignition chamber built into its head with a spark plug and spray nozzle inserts for an initial reduced flow of fuel and oxidizer. Later a hypergolic starting fluid was used on the RD-1KhZ. The engine could be restarted several times. The TCs were regeneratively cooled by acid. The design for thermal expansion of the outer chamber wall for all three of these aircraft rocket engines was accomplished by using belleville springs on the bolts holding the chamber and nozzle portions together. Some versions had a bellows-type expansion joint in the outer wall. Injection was by spray nozzles made of stellite with spiral inserts, and they included small spring-loaded check valves to minimize the dribble volume and limit backflow. In a later modification, the use centrifugal pumps and electropneumatic controls was tested on an RD-3 engine.

It was already mentioned that RNII ground tested a turbopump fed LPRE in 1945, before the details of the TP of the German V-2 engine became available to the Soviets. The TP had a single-stage turbine, a reduction gear, an oil lubrication unit, a centrifugal acid pump, a centrifugal fuel pump, and a water pump. The gas temperature and, thus, the thrust were controlled by the flow of the water–alcohol mix to the GG. The thrust was controlled by the pilot's engine lever with mechanical linkages to the main propellant valves and the GG water–alcohol valve. The engine came in two packages: a TC/valve package and a TP/GG package with the three propellant start tanks and their pressurizing system. The two packages could be installed in different parts of the airplane. One experimental version of these aircraft rocket engines used a hydrogen peroxide monopropellant GG; this feature was picked up from the Germans and simplified the engine system and the restart operation.

A lighter weight version of this first Soviet self-contained (independent of external power) aircraft rocket engine with a TP, a GG,

Table 2 LPRE Design Bureaus and R&D Institutes

Organization name	Location	Area of specialty
NPO Energomash (identified with academician Valentin P. Glushko)	Khimki, Moscow Region	High-thrust LPREs for first and second stages of ballistic missiles and space launch vehicles
KB Khimmash (Design Bureau of Chemical Machinery) originally Isayev DB; (KB is Russian acronym for DB) (Isayev DB)	Korolev, Moscow Region	Upper stage LPREs for ballistic missiles or SLVs, engines for submarine-launched ballistic missiles (SLBM), short-range ballistic missiles; reaction control thrusters and space engines
Chemical Automatics Design Bureau (CADB), originally S. A. Kosberg DB, or KB Khimautomatiki; CADB	Voronezh, Russia	Upper stages of SLVs and ballistic missiles, built one SLBM engine, and LOX/LH_2 LPREs
NII Mashinostroyeniya (R&D Institute of Mechanical Engineering)	Sverdlovsk Region, Russia	Reaction control thrusters for spacecraft and orbiting stations
NK Engines (N. D. Kuznetsov DB) (Samara Science and Technical Complex)	Samara (formerly Kuibychev), Russia	Jet and aircraft engines, in past some large LPREs
RKK Energiya (was Korolev DB) RKK means Rocket and Space Corporation	Kalingrad, Moscow Region	Launch vehicles and spacecraft; also some upper-stage LPREs and vernier LPREs
Lyulka Engine DB (Saturn Science and Production Association)	Moscow	Gas turbine aircraft engines, power supplies; in past also developed LOX/LH_2 engine
Southern Machine Building Production Association, included Yuzhnoye DB	Dniepropetrovsk, Ukraine	Vernier and upper-stage engines for SLVs, spacecraft, and missiles, and postboost vehicle control.
Keldysh Institute for Applied Mechanics (originally part of RNII)	Moscow	R&D and analysis on all types of propulsion and flight vehicles, mission analyses/optimization
State Institute of Applied Chemistry	Leningrad	Develop, characterize, synthesize new propellants and their production processes

multiple restarts, and throttling was flight tested on a piloted experimental fighter aircraft I-270 beginning in September 1947. For comparison, the Germans had flown an experimental monopropellant turbopump-fed aircraft rocket engine (with GG) in 1940 and a bipropellant LPRE with a TP in 1943.

The Kosberg Design Bureau [Chemical Automatics Design Bureau (CADB)] and the KB Khimmash DB (see Secs. VII.B and VII.C) also undertook the design and development of several other aircraft superperformance LPREs in the late 1940s and early 1950s. Several of the aircraft rocket engines were also tested as jet assisted takeoff (JATO) engines on some of these airplanes. The CADB RD-0101 using LOX/ethyl alcohol and was flown in the E-50A aircraft and the RD-0102 with a thrust of 4 tons using LOX/kerosene, and chemical ignition was flight tested in a Yak-27V fighter airplane. Thereafter, this LPRE was produced in limited quantities, installed in a group of Yak-27V fighters of the Soviet Air Force for operational evaluation. The Soviets have flight tested their aircraft rocket engines in about a dozen different military airplanes, more than any other nation.

The flight tests showed that rocket power could be harnessed in aircraft, could dramatically shorten the time to climb to high altitude, and sometimes could enhance flight maneuverability. However, they greatly reduced the aircrafts' range and payload. These Soviet aircraft rocket engines did not usually reach the intended reliability and design life (typically 45 h of flight and 100 starts), and there were dramatic accidents. According to one source, the Soviet Air Force was never really satisfied with these engines, and none of the fighter airplanes equipped with rockets were ever used in combat. Although Russia no longer produces rocket engines for military aircraft today, the development of these engines helped to build a viable LPRE capability and constitutes a significant accomplishment in early Soviet LPRE history.

VII. Organizations Working on LPREs in Russia and Former Soviet Union with Some of Their Key Engines

Beginning around 1939, the Soviet government wanted to broaden the LPRE capability of the country and several new Design Bureaus for LPREs were established.[7,9,12,18–22] The Design Bureau (DB) is a unique Soviet organization where complex hardware is engineered and developed, but not produced in quantity. The DBs were responsible for the R&D of LPREs, their testing, and their experimental fabrication, but not their serial production. The DBs were often named after their chief designers, but name changes and reorganizations of these bureaus were quite common.[7,18–20] Each DB normally had the facilities to conduct laboratory tests and manufacture and test its own experimental LPREs and their components, and some had special facilities for simulated altitude tests or housing and medical facilities for employees and their families. Several of these LPRE DBs worked also on other military hardware (such as turbojet engines, aircraft components, missiles, or SLVs), and for some of these, the rocket engine business was a side line. The list of DBs developing LPREs in Table 2 is not complete because there were some others.[9,21,22] Of those listed, only one is outside of Russia today. Some universities and government R&D institutes/laboratories also conducted R&D related to LPREs, and they worked with the DBs.[23] Two such institutes are listed in Table 2.

The first three DBs and a few of their historic LPREs will be discussed in an abbreviated way in the next three sections, and then the other DBs will only be briefly mentioned. This summary article describes only a few of the more than 500 engines and concentrates on those that have some historical significance. A future book by this author will discuss all the major LPRE DBs, some of the engines described here in more detail, and include more historic and interesting other LPREs. The book is currently scheduled to be published by the AIAA late next year

How did a DB get work? The decisions on awarding vehicle and LPRE development jobs to specific DBs was often the result of interactions between lead personalities. Once a vehicle or system's lead designer was comfortable with a lead designer of a LPRE DB and satisfied with the prior engine products received, it was not unusual to see continued reliance on that LPRE bureau for that class of engines. For example, all but one of the LPREs for submarine-launched missiles were developed by the same DB.

The Soviet LPRE activity increased greatly in the 1960s and reached a peak in the 1970s. This was the period of the cold war between the Soviet Union and the United States and the competition for spaceflight achievements. At that time, between 12 and 16 DBs and R&D institutes were involved in developing LPREs. In the last 25 years, the engine development effort has diminished, not

Table 3 Examples of LPRE production plants

Name	Location	Example of Assignment
Metallist Samara OAO	Samara, Russia	TCs for RD-253
Ust-Katav Wagon Building Plant	Ust Katav, Ural Region, Russia	KB Khimmash engines, some work for CADB
Perm Motor Production Plant	Perm, Russia	Assembly of RD-216
NPO Motorostroitel	Samara, Russia	RD-107/108 family
Voronezh Mechanical Plant	Voronezh, Russia	Production of engines designed by CADB
Krasnoyarsk Machine Building Plant (Krasmash)	Krasnoyarsk, Russia	LPREs for spacecraft and SLBM of KB Khimmash
YuyzhMash Plant or Southern Machine Bldg. Production Plant	Dniepropetrovsk, Ukraine	RD-120, vernier engines
PO Poliot	Omsk, Russia	RD-170/171
Krasnaya Oktobr	Leningrad	Surface-to-air missiles (SAMs) LPREs, RD-0235/0236

just in the Soviet Union, but also in other countries. The number of Soviet or Russian organizations seriously working on LPREs has shrunk to less than half, and several of the currently existing DBs are working with about half their former staff levels. In some DBs, only some of the current personnel are engaged in LPREs because they have started conversion products (such as commercial pumps or oil field equipment). They have recently been encouraged by their government to export LPRE technology and hardware.

Production usually took place in one of the independent production plants, dedicated to this purpose.[9] A partial list is in Table 3. Many of these plants were known by other names, have been reorganized, and may have been diverted to other work. The cognizant DB maintained a group of engineers at the production plant. A production plant has the right to redesign parts of a LPRE to make the hardware more producible, but the DB has to certify that the proposed change does not compromise its function. Only one of the listed plants is at this time outside of Russia.

At the end of World War II, the Soviet rocket propulsion effort was given a big boost when information on much of the secret propulsion work developed in Germany during World War II became available. In 1945, the Germans were probably 10 years ahead of the Soviets in their LPRE technology. The V-2 production plant, which was located in the Soviet zone of Germany, was refurbished, rebuilt, and reactivated. A large number of these V-2 missiles were actually built first in Germany and then in Russia, and many were launched, beginning in 1947. The Soviet Union also obtained the assistance of two groups of Germans.[24] One group of engineers from Peenemünde of about 200 specialists conducted studies and prepared preliminary designs of advanced weapon systems for the Soviets. The other larger group consisted mostly of production and launch personnel, and they helped with the Soviet production and testing. The Germans never learned what missiles and engines the Soviets themselves were developing on their own. After 4–7 years (often under uncomfortable conditions), the groups of Germans were allowed to go home. The returning Germans downplayed the value of their contributions to the Soviet missile and pace effort, in part, because they did not receive any feed back as to the use or value of their studies. However one reference[24] states that the benefits to the Soviets were considerable.

A. NPO Energomash

The history of this DB can be traced back to the GDL and its successor the RNII, the prewar rocket engine organizations, mentioned in Sec. V.[7,9,12–14] Energomash is best known for its many large LPREs.[18–31] From its beginning, the chief designer was Valentin P. Glushko, considered by many as the key individual in Soviet large LPRE developments.[14,18,19] During the Stalin purges, a significant number of the intelligentsia were arrested on trumped up charges and deported. In 1938, Glushko and some other key people were arrested and sent to a prison camp. A year later he was allowed to continue his work on LPRE, while in captivity. Glushko managed to assemble a small engineering group, which soon was moved to a factory in Kazan (700-km east of Moscow), and there he officially formed a small experimental DB, but under guard. They developed small LPREs including the RD-1 for aircraft mentioned in Sec. VI. They were released from prison in 1944. Glushko was later selected to become an associate member and a few years later a full member of the U.S.S.R. Academy of Sciences, and in the late 1960s until the early 1970s he was actually in charge of all of the Soviet space and ballistic missile development efforts.[14]

In 1946, his LPRE R&D organization was relocated into an aviation plant at Khimky, a densely populated part of the Moscow Region. The test facilities for large LPREs were constructed indoors because of the weather and the adjacent housing. Unique test facilities were developed to control the hot toxic exhaust vapors and reduce the loud noise characteristic of large engines and their exhaust plumes. The engines fired vertically downward into a large (vertical axis) vortex chamber with intensive water sprays to scrub and cool the hot gas. The cooled and cleaned gas is ducted away from the test stands (by means of ejectors) in large horizontal ducts and exhausted through tall chimneys.

The name Energomash was adopted in 1967. Table 4 provides some data on 30 of their LPREs.[2,7,18,21,22,25–30] By this DB's own count, there were altogether 95 LPREs, of which 35 passed qualification tests and 30 have flown. Only some of the engines listed in Table 4 are discussed in this summary paper.

In Moscow, Glushko and his people originally worked in 1946 on improving the German V-2 engine, but soon they developed several engines that were at higher thrust and represented a significant improvement over the V-2.[25–27] Instead of the 18 separate injection domes and a nearly spherical chamber of the V-2, they used flat injectors (no dome) and then a single-dished multiple-plate injector with a more slender chamber. They started with the German propellants LOX/75% ethyl alcohol. The Soviet made a slightly modified copy of the V-2 engine, and two of the early Soviet uprated and greatly improved versions of the V-2 LPREs were actually put into production for short-range and medium-range Soviet ballistic missiles, which were deployed. They also built several experimental thrust chambers (up to 7-metric tons thrust), and these were most useful for investigating various cooling methods, cooling jacket designs, injector designs, starting techniques, and other parameters.

The first major and truly historic new Soviet engines put into production were the RD-107, shown in Figs. 10 and 11, and its companion engine the RD-108, which is described later. They are well documented[7,12,18–22,26,27,29,31] and described here in somewhat more detail. The RD-107 has four fixed (not movable) TCs, two hinged vernier TCs supplied by the same feed system, one TP, and one monopropellant hydrogen peroxide gas generator with a pebble type solid catalyst. Data are given in Table 4.

These historic engines have been originally used on the R-7 intercontinental ballistic missile (ICBM) and later on the Vostok, Voshkot, Molniya, and Soyuz families of SLVs. Engine development started in 1953/1954, the first engine test with a single TC occurred in 1955, and the test with four TCs occurred in 1956. It

Table 4 Data on selected LPREs of Energomash

Designation	Thrust (SL)/vacuum (V), kN	No. of TCs per engine	Specific impulse, s	Propellants	Chamber pressure, kg f/cm^2	Engine mass kg	Height/ diameter, m	Development period, years	Application and comments
ORM-65	1.72 (SL)	1	215 (SL)	HNO_3/kerosene	25.5	14.3	0.46/0.38	1936	RP-318 glider, winged rocket
RD-1	2.94 (SL)	1	200 (SL)	HNO_3/kerosene	21			1941–1945	Flew on Pe-2, La-7, Yak-3 and Su-6 aircraft
RD-1 KhZ	2.94 (SL)	1	200 (SL)	HNO_3/kerosene	20.4	14.3	0.85/0.4	1941–1946	Flew on Pe-2R, Yak-3, La-7R, La-120R, Su-6, and Su-7 aircraft
RD-100	257 (SL)/304 (V)	1	199 (SL)/233 (V)	LOX/75% alcohol	16.2	1,209	3.7/1.65	1946–1950	R-1 SRBM, copy of V-2
RD-101	363 (SL)/404 (V)	1	210 (SL)/237 (V)	LOX/92% alcohol	21.6	1,178	3.54/1.65	1946–1951	R-2(SS-2) SRBM
RD-103M	432 (SL)/500 (V)	1	432 (SL)/500 (V)	LOX/92% alcohol	21.1	1,867	3.22/1.65	1946–1953	R-5M(SS-3 Mod 2) MRBM
RD-107	814 (SL)/1000 (V)	4/2	256 (SL)/313 (V)	LOX/kerosene	60	1,190	2.86/1.85	1954–1957	First stage R-7 ICBM, and R-7A for SLVs,[a]
RD-108	745 (SL)/941(V)	4/4	250 (SL)/316 (V)	LOX/kerosene	52	1,625	286/1.85	1954–1958	Second stage for same vehicles
RD-111	1412 (SL)/1628 (V)	4	275 (SL)/317 (V)	LOX/kerosene	80	1832	2.1/2.74	1959–1962	First stage R-9A (SS-8) ICBM
RD-119	105 (V)	1	352 (V)	LOX/UDMH	80	107.2	2.17/0.96	1958–1962	Second stage of Kosmos 2 SLV
RD-120	833 (V)	1	350 (V)	LOX/kerosene	166	1,125	3.87/1.95	1976–1985	Second stage of Zenit and Zenit 3 SLVs
RD-120 K	77.9 (SL)/88.7 (V)	1	295 (SL)/336 (V)	LOX/kerosene	187	1,037	2.53/1.54		Improved RD-120, has not flown
RD-170	7257 (SL)/7904 (V)	4	309 (SL)/337 (V)	LOX/kerosene	250	10,750	4.0/4.0	1976–1987	First stage of Energia SLV
RD-171	7257 (SL)/7904 (V)	4	309 (SL)/337 (V)	LOX/kerosene	250	NA	4.0/4.0	1976–1987	RD-170 adapted for Zenit 2, Sealaunch
RD-180	3824 (SL)/4148 (V)	2	311 (SL)/338 (V)	LOX/kerosene	261.7	5,330	3.58/3.2	1992–1998	First stage of Atlas 3 SLV, two-chamber derivative of RD-170/171
RD-191	1922 (SL)/2085 (V)	1	310 (SL)/337 (V)	LOX/kerosene	263.4	2,200	4.0/1.45	1998	Single chamber derivative of the RD-170, RD-180; not yet flown, proposed for Angara SLV
RD-214	636 (SL)/730 (V)	4	230 (SL)/264 (V)	HNO_3/kerosene	44.5	645	2.38/1.5	1952–1957	R-12 (SS-4) MRBM; first stage of Kosmos 2
RD-216[b]	1481 (SL)/1677 (V)	4	246 (SL)/289 (V)	HNO_3/UDMH	75	1,350	2.19/2.26	1958–1960	RS-14 (SS-5) MRBM or IRBM?
RD-218[c]	2221 (SL)/2608 (V)	6	246 (SL)/289 (V)	HNO_3/UDMH	75	1,960	2.2/2.8	1958–1961	First stage of R-16 (SS-7) ICBM
RD-219	883(V)	2	293 (V)	HNO_3/UDMH	75	760	204/2.2	1958–1961	Second stage of R-16 ICBM
RD-251[d]	2363 (SL)/2648 (V)	6	270 (SL)/301 (V)	NTO/UDMH	85	1,729	1.7/2.52	1961–1965	First stage R-36 (SS-9) ICBM
RD-252	902 (V)	2	317.6 (V)	NTO/UDMH	91	NA	NA	1961–1966	Second stage R-36 and Tsyklon
RD-253	1471 (SL)/1638 (V)	1	285 (SL)/316 (V)	NTO/UDMH	150	1,080	3.0/1.5	1961/1965	First stage Proton SLV (6 engines)
RD-264[e]	4168 (SL)/4521 (V)	4	293 (SL)/318 (V)	NTO/UDMH	210	3,600	2.15/3.0	1969–1973	First stage R-36M (SS-18 Mod 1–3) ICBB
RD-268[f]	1147 (SL)/1236 (V)	1	295.6 (SL)/318.5 (V)	NTO/UDMH	230	770	2.15/1.08	1969–1976	First Stage of MR-UR-100 ICBM
RD-270	6276 (SL)/6717 (V)	1	301 (SL)/322 (V)	NTO/UDMH	266	4,770	4.85/3.3	1962–1971	Development not completed
RD-275	1590 (SL)/1745 (V)	1	289 (SL)/316 (V)	NTO/UDMH	163	1,070	3.0/1.5	1996	Improved RD-253 for Proton-KM, not yet flown
RD-301	96.1 (V)	1	400 (V)	LF_2/NH_3	120	183	1.89/0.98	1969–1977	Upper-stage experimental engine, program abandoned
RD-701		2				3,800	5.0/5.0	1988	Tripropellant experimental engine, not yet qualified
Mode-1	3920 (SL)		415 (SL)	LOX/LH_2/kerosene	300				
Mode-2	1590 (V)		460 (V)	LOX/LH_2	122				
RD-704		1				2,000	5.0/2.3	1988	Tripropellant experimental engine, not yet qualified
Mode-1	2040 (SL)		415 (SL)	LOX/LH_2/kerosene	300				
Mode-2	810 (V)		461 (V)	LOX/LH_2	122				

[a] Vostok, Voshkod, Molniya, and Soyuz.
[b] Consists of two RD-215 each with two TCs and single TP, and GG engine cycle.
[c] Consists of three RD-217 engines, each with two TCs and one TP, it is improved RD-215.
[d] Cluster of three RD-250 engines, each with two TCs and one TP; first stage of Tsyklon SLV.
[e] Consists of four RD-263 engines, each with its own TC and TP.
[f] Derived from RD-263.
SL = See level condition; SLV = Space launch vehicle; SRBM = Short range ballistic missile; MRBM = Medium range ballistic missile.
ICBM = Intercontinental ballistic missile; NTO = Nitrogen tetroxide; UDMH = Unsymmetrical dimethyl hydrazine.

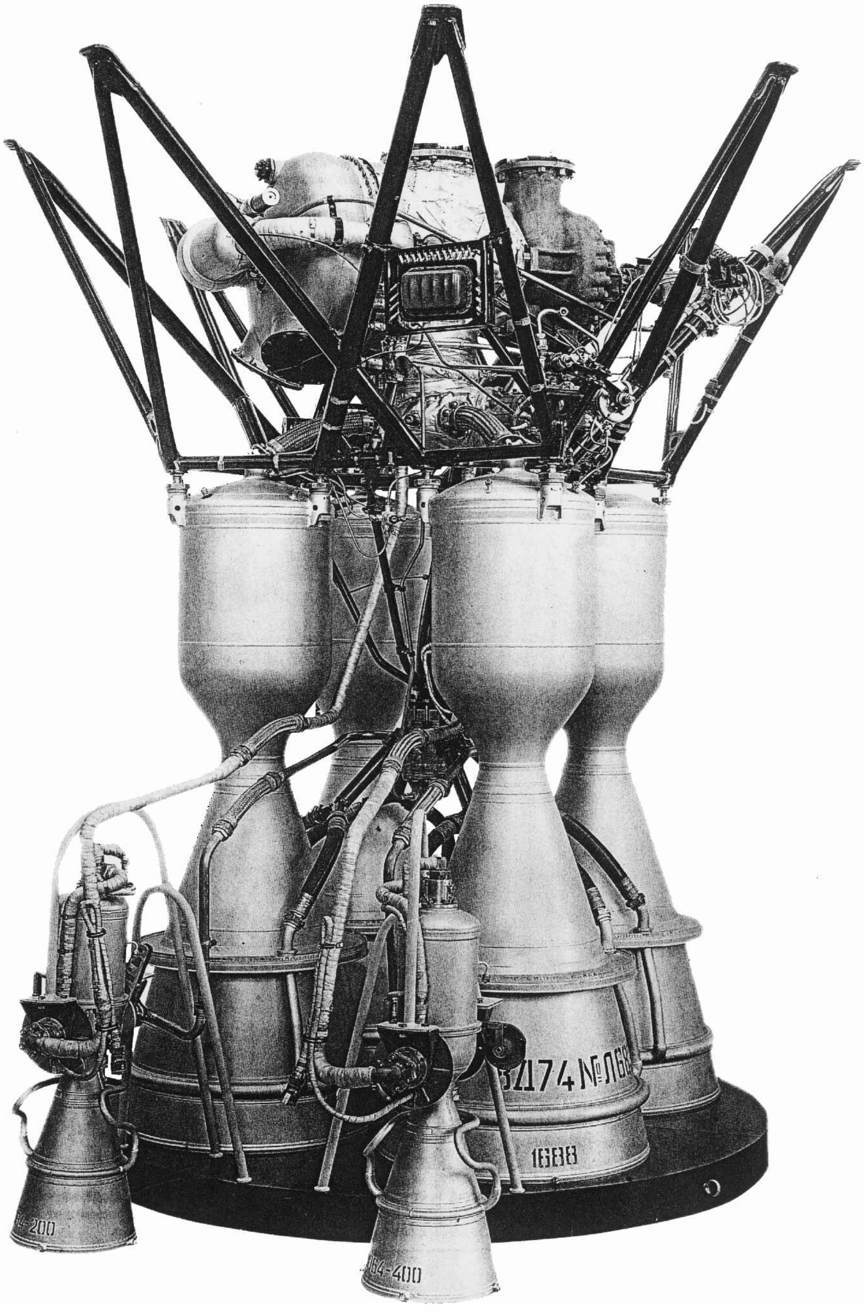


Fig. 10 RD-107 LPRE is typical of Soviet state-of-the-art technology in the 1950s (courtesy Energomash).

is the world's most utilized booster rocket engine and one of the longest living active large LPRE programs. At the end of 2001, over 1630 vehicles had been launched with the production models at a success rate of 97.5%. Its first successful space launch with five engines (20 TCs) was Sputnik in 1957.

The compact TP of the RD-107, shown in Fig. 12, has two in-line shafts, each with two ball bearings, a concept acquired from the German V-2 TP. The sleeve-type flexible coupling with internal splines connecting the two shafts is smaller and lighter than the German flange coupling. The merits of the two in-line shaft design are smaller diameter lighter shafts, often smaller diameter lighter housings, and smaller more durable bearings and seals. The disadvantage are a more complex unit (more seals, bearings, and a coupling) and often a longer TP assembly, which can be more difficult to package into an engine or a vehicle. The TP has a steel turbine with two rows of blades, a shrouded double inlet oxygen impeller, a single-sided fuel impeller, and a gear case through which small pumps for the hydrogen peroxide and liquid nitrogen are driven. The liquid nitrogen is gasified by flowing through the heat exchanger located in the turbine exhaust gas assembly and then used for pressurizing the main propellant tanks. The hydrogen peroxide is decomposed by a solid catalyst to form steam and hot oxygen, which provide the power for the turbine.

The four TCs are regeneratively cooled by kerosene and have two different cooling jacket designs.[31] The inner wall and the outer wall are connected by a corrugated intermediate wall in the chamber and nozzle exit sections, as shown schematically in Fig. 13a. The corrugations define the flow passages for the coolant fluid, and different corrugation patterns may be used within the same cooling jacket. At the nozzle throat region, where the heat transfer is the highest, the RD-107 has a different cooling jacket configuration with an inner wall made of a higher conductivity metal alloy. As shown in Fig. 13b, the inner wall has integral vertical ribs, which form the flow passages. This channel wall piece is brazed to the

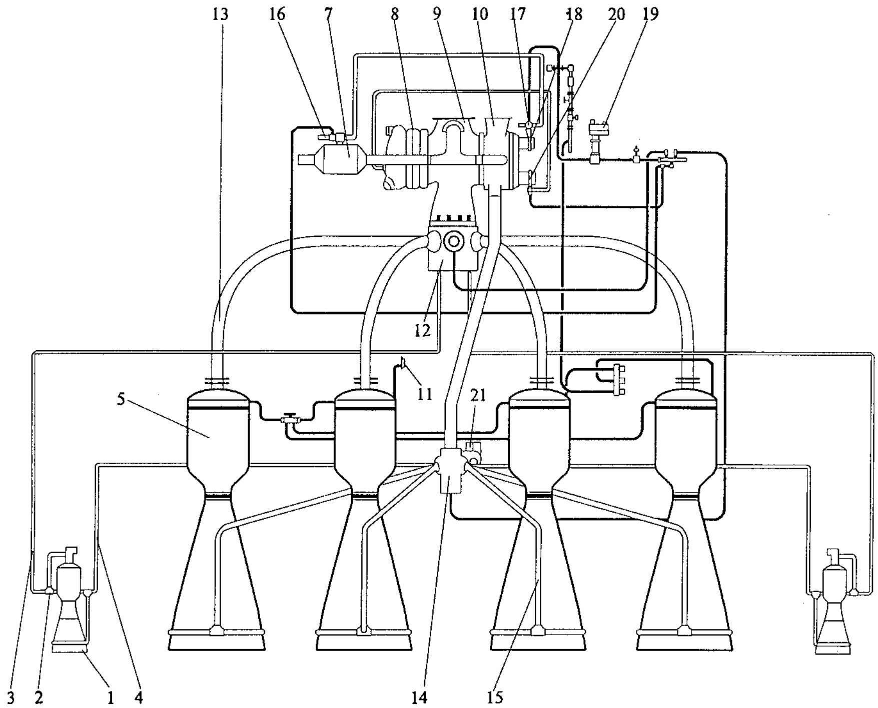


Fig. 11 Simplified flow diagram of the RD-107[9,22]: 1) steering chambers, 2) steering chamber rotary unit, 3) oxidizer manifolds, 4) steering chamber fuel manifolds, 5) main combustion chambers, 7) GG, 8) turbine, 9) oxidizer pump, 10) fuel pump, 11) TC system pressure sensor, 12) main oxidizer valve, 13) main chambers oxidizer manifold, 14) main fuel valve, 15) fuel manifold of main chambers, 16) hydrogen peroxide valve, 17) pressure reducer, 18) hydrogen peroxide pump, 19) motor-powered pressure reducer, 20) liquid nitrogen pump, and 21) system throttle.

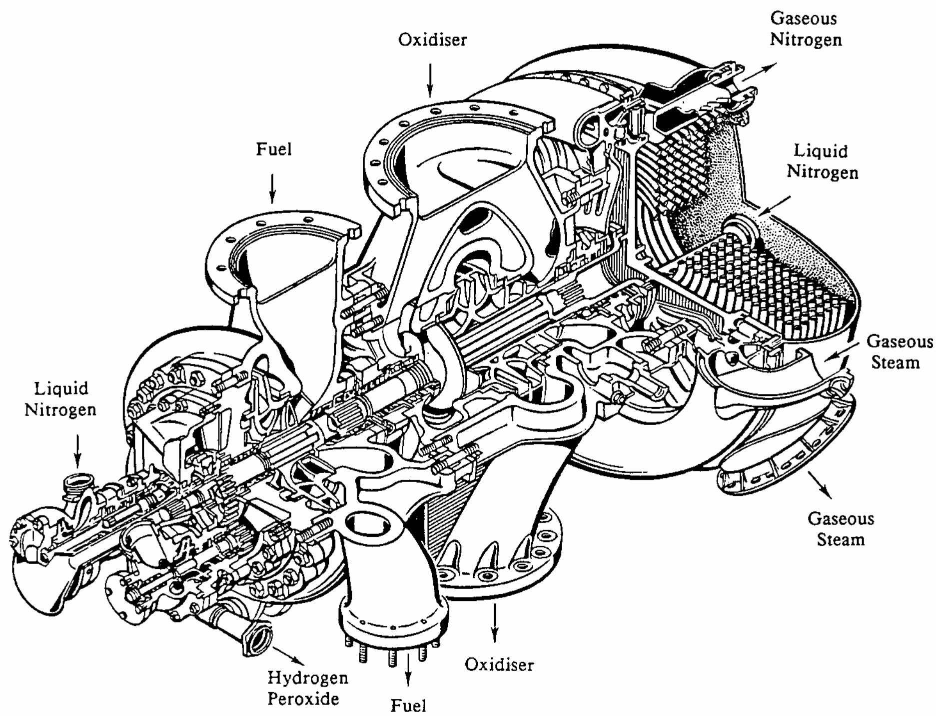


Fig. 12 Sectioned diagram of TP of RD-107 (courtesy Energomash).

outer stainless steel wall, and both the inner and the outer walls of this throat piece are welded to the corrugated jacket configurations above and below it.

All of these three-dimensional precision-formed metal sheets are coated with a manganese-based brazing material on the appropriate surfaces and are assembled together in a fixture. Brazing is done in a furnace with an inert atmosphere or a vacuum and good brazing requires precision parts, accurate fixtures, and close fits of the sheet metal parts. The various pieces of the inner and outer wall are precision welded together, and this also requires very good fits.

The unique Soviet design with the intermediate corrugated wall was developed between 1948 and 1951. A similar cooling jacket wall construction has been and is used in many Soviet TCs including those of other DBs. Many of these (particularly at low chamber pressure) use the corrugated designs also in the throat region. It is a unique lightweight Soviet cooling jacket design not found elsewhere. The tubular cooling jacket design of Fig. 13c originated independently in the United States at about the same time, has served for the same applications, and has been used in most countries, except Russia. Depending on the design details, the Soviet design with corrugated sheet metal for flow passages, can be lighter in mass than the tubular design.

The RD-107 injector, shown in Fig. 14, has an outer welded dome-shaped metal cover (on top of the oxidizer distribution cavity), an intermediate bulkhead or middle plate (which separates the fuel and oxidizer manifolds), and a flat inner wall, which is the face of the injector. Many short steel tubes (called injection elements or also injection nozzles) at right angles to the injector face connect the middle and inner plates, and they are brazed in place. Offset small tangential inlet holes in the tubes create a vortex or swirl flow of the oxygen and the fuel flows inside the tubes, where the propellants are then discharged and form conical propellant sprays. There are 337 such tubes or injection spray points, arranged in 10 rings. The outer rings spray only fuel on the inner chamber wall (film cooling) and keep the wall temperature below 380°C. Energomash encountered high-frequency combustion instability during development, but it was remedied by design changes in the injector. The Soviets have used these spray inserts in almost all injectors, in part, because they give good performance and they have had favorable experience since the 1930s. This author did not find many Soviet injectors of flying LPREs with drilled holes or impinging streams of propellant, which have been used frequently in other countries.

Figure 15 shows a view of the aft end of the Soyuz SLV, which is a modified version of the R-7 ICBM missile. There are four strap-on, drop-off boosters, each equipped with one RD-107, and a center core RD-108 engine, which is quite similar to the RD-107, except it has four hinged vernier TCs, and runs at a lower chamber pressure, for a longer duration and at a somewhat lower thrust. Altogether there are 20 large TCs and 12 smaller vernier TCs, for a total of

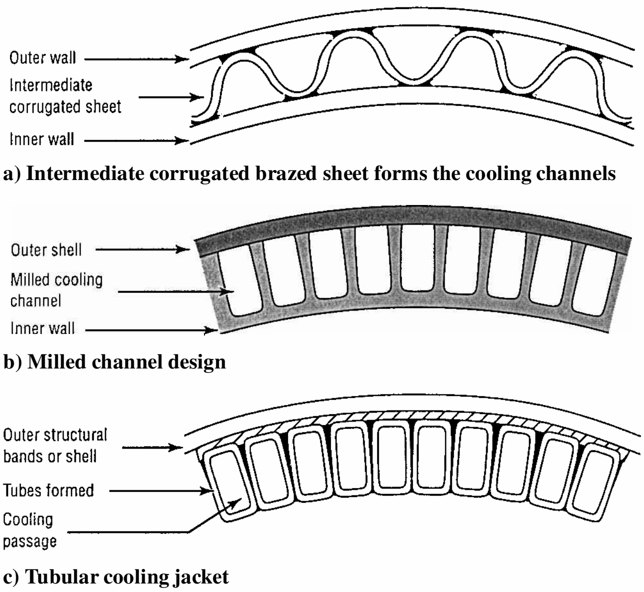


Fig. 13 Cross sections of three common types of cooling jackets; tubular design shows an optional filler layer, which is often deleted.

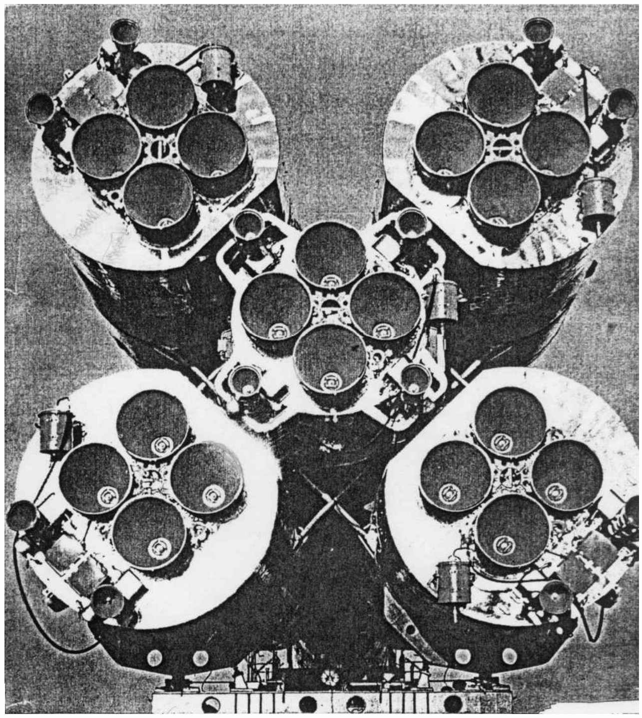


Fig. 15 Soyuz SLV with an RD-107 in each in the four droppable, external booster assemblies, and a center RD-108, which starts at the same time, but operates for a much longer time.

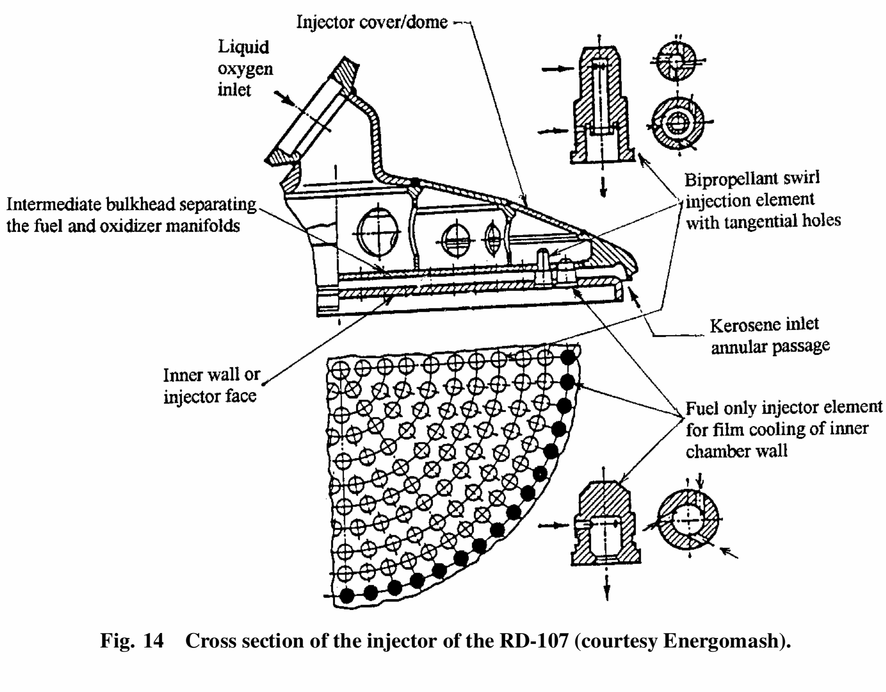


Fig. 14 Cross section of the injector of the RD-107 (courtesy Energomash).

32 nozzles. There may be as many as 17 different versions of these two LPREs, and many have slightly different performance numbers than is stated in Table 4.

The vernier TCs for the RD-107/108 were originally assigned to the Korolev DB, in part, because Glushko's DB was busy. Korolev's DB developed the S1 35800 to fit this need. When the requirements changed (switch from an ICBM to a SLV) then Energomash developed the higher performance TC, and Glushko then had the complete engine assembly in his organization. The thrust of a hinged vernier TC for the RD-107 is about 38 kN (SL). The technology and the S1.35800 hardware were transferred to CADB, where it was uprated and eventually became the RD-0105 LPRE.

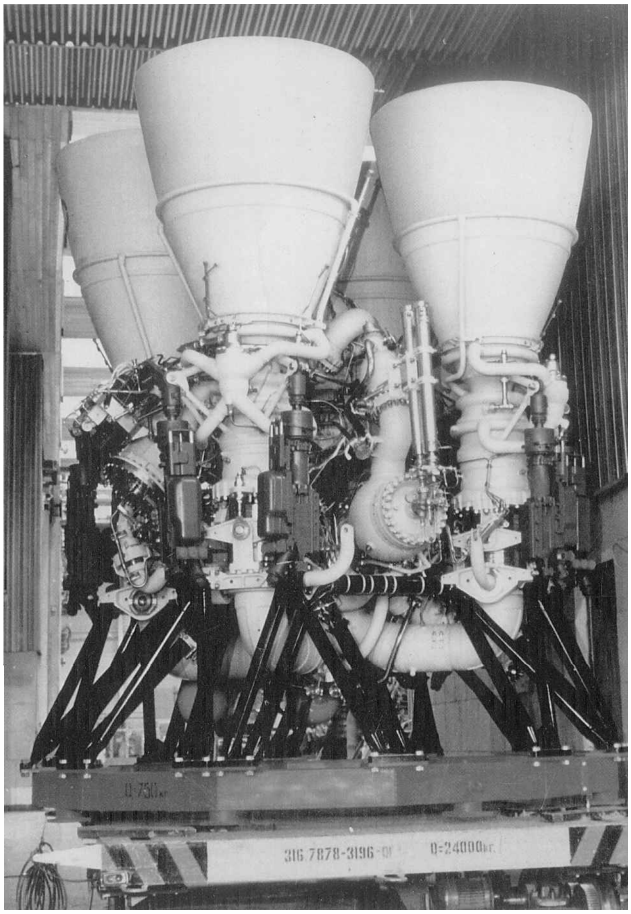


Fig. 16 RD-170 has the highest thrust of any LPRE, upside down on a cart (courtesy Energomash).

The RD-120 second-stage engine uses LOX and kerosene, has a staged combustion cycle, and features a high nozzle area ratio of 106:1 and ignition by an initial small quantity of hypergolic fuel.[2,26,28,30] It has a thrust structure around the nozzle because this particular engine is mounted on a fixed thrust structure in the middle of a large toroidal tank in the second stage of the Zenit launch vehicle. The first flight was in 1985. This engine has been licensed to Pratt and Whitney Aircraft, United Technologies Corporation (P& W) for potential sales in the United States and was tested by P&W in Florida in 1995, but a U.S. application was not found.

The RD-170 has the highest thrust in the world (7904 kN or 1.77×10^6 lbf in vacuum), slightly higher than the retired older U.S. F-1 engine (1.5×10^6 lbf). It is a historically significant engine and deserves a more detailed description. It has a relatively very high chamber pressure listed in one version as 242 atm (3550 psia) (Refs. 21 and 26–30). The RD-170 has four hinged TCs, a single large 14,500-rpm TP of 250,000 hp, and a staged combustion cycle with two oxygen-rich spherical preburners. This LPRE and its flow sheet are shown in Figs. 16 and 17. The photograph (Fig. 16) shows a relatively high nozzle expansion area ratio of 36.8 to 1.0, a tube structure to transfer the major thrusts, and a hinge actuator (dark color). Only two of the four TCs are shown in the schematic diagram (Fig. 17). The main TP has a single-stage turbine and two fuel pumps, but only one oxygen pump. The long shaft is indicated by a black line in the flow sheet. The two booster pumps help to prevent cavitation, and one of them has a hydraulic turbine.

Figure 18 shows a thrust chamber of a type used in the RD-170. It is regeneratively cooled with fuel and uses supplementary film cooling, and its assembly is done both by brazing and welding of the parts.[11,26,27] The kerosene fuel at ambient temperature is fed into the cooling jacket just upstream of the nozzle, where the heat transfer is the highest. The intensive heat is absorbed without the formation of detrimental carbon deposits, which would impede heat transfer and cause excessive wall temperatures. External piping is used in this relatively complex cooling jacket. The cooling channels, as seen in cross section in Fig. 19, are essentially rectangular and straight, except in the converging nozzle section, where the rectangular channels are arranged in a helical flow pattern. Figure 19 also shows the 271 injection elements, which are of two basic types as shown in Fig. 20. One protrudes beyond the injector face. Examination Fig. 19 reveals that 54 of these protruding elements (shown by

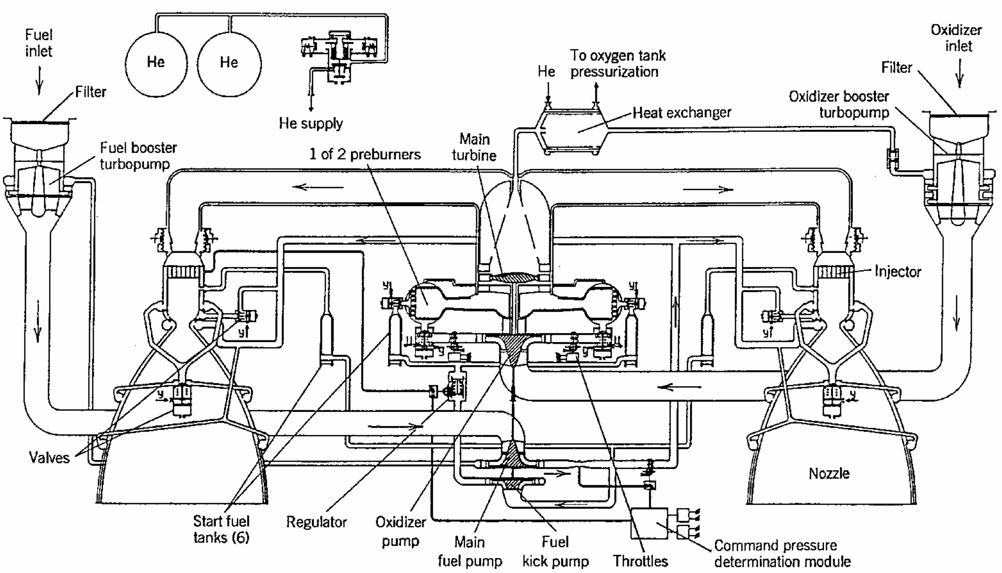


Fig. 17 Simplified flow diagram of the RD-170 (courtesy Energomash).

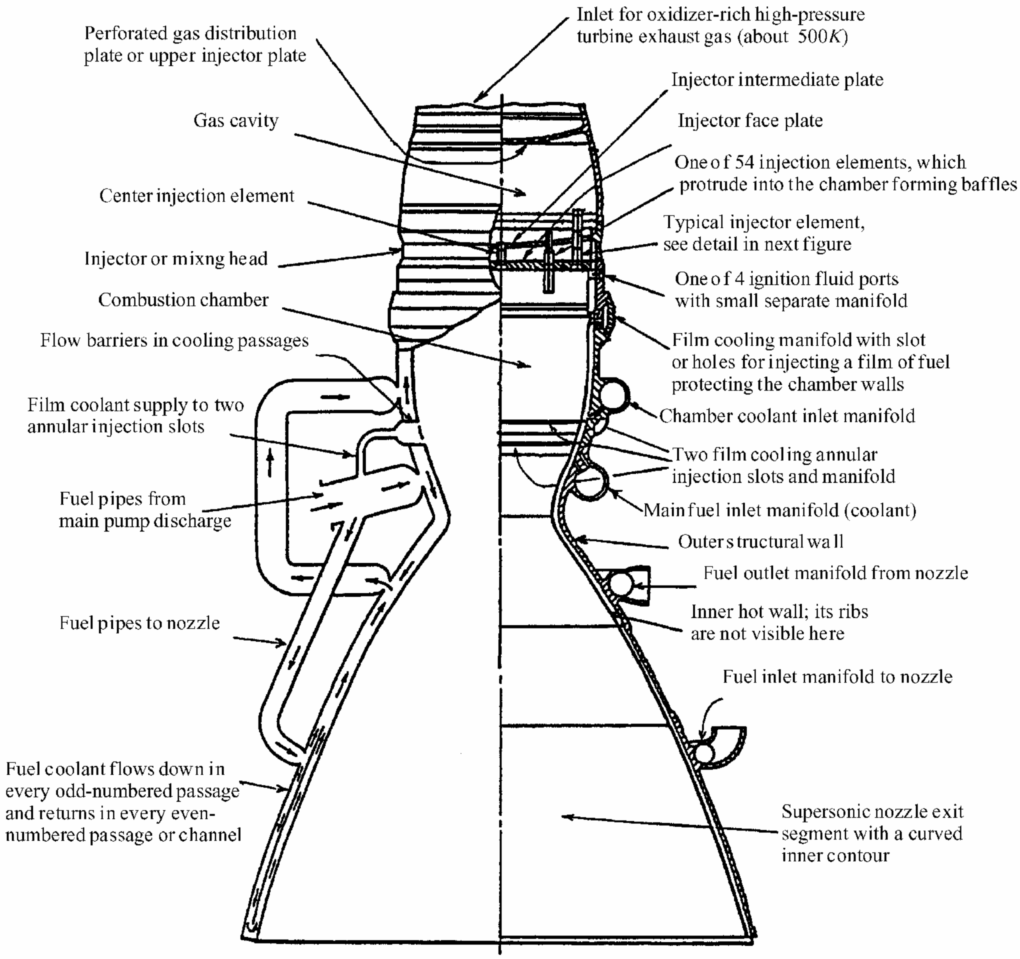


Fig. 18 TC is similar to the RD-170 TC, fuel flow circuit is on left and cross section is on right (adapted from an Energomash patent drawing).[11]

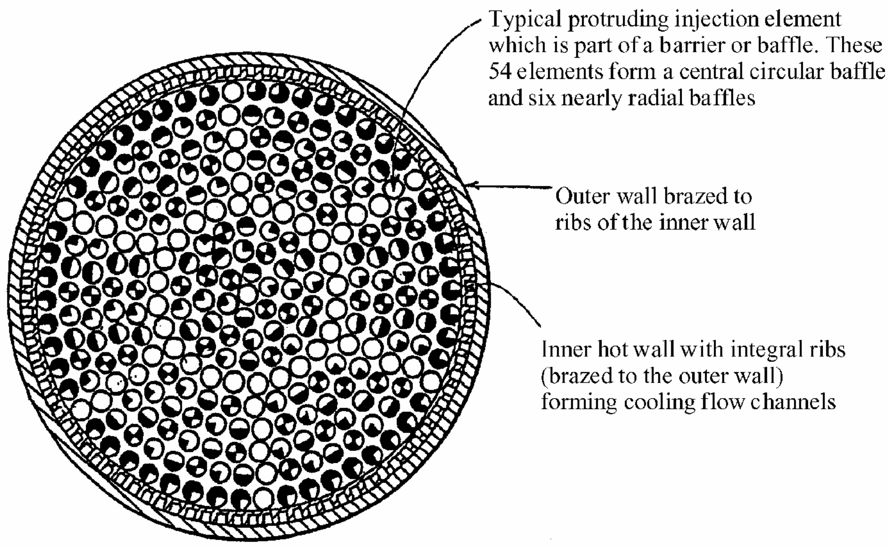


Fig. 19 Front view of the injector face and section of the cooling jacket of the TC shown in Fig. 18 (adapted from Energomash patent).[11]

simple small circles) form antivibration baffles, namely, a circular central baffle and six nearly radial baffles. The baffles are not in a continuous wall, but have gaps between protruding injection elements. These gaps cause extra damping to an oscillating flow. The other injection elements shown in Fig. 20 each end at a countersunk recess of the injector inner face plate. There are four slightly different detail designs with four different mixture ratios. The amount of black color in the circles of Fig. 19 (one-quarter, one-half or three-quarter black) designates different mixture ratios: The more black area, the more oxidizer rich is the mixture ratio of that element. The oxidizer-rich gas flows through the injection elements in an axial direction, but the fuel is injected through tangential holes, forming a vortex in the annular space of the injection element and emerging from the element in a conical spray redundant. The distribution of the different types if injection elements on the injector's face is not random, but generally follows spiral type patterns, as can be seen

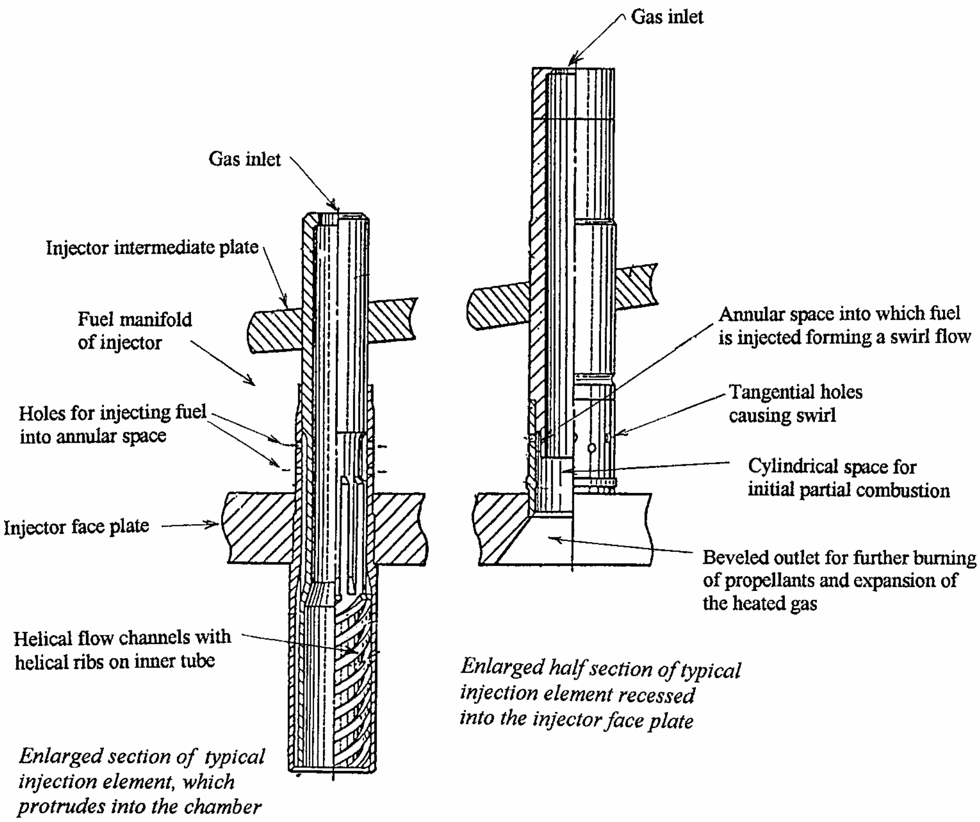


Fig. 20 Two typical injection elements of Fig. 19 (from Energomash patent).[11]

on Fig. 19. The variations of the four groups of injection elements in their flow rates, their mixture ratios, and their placement on the injector face are needed to avoid high-frequency combustion instability over the operating range. The inner wall material is a copper alloy with relatively high thermal conductivity, and the outer walls, manifolds, and pipes are stainless steel. The injection elements are brazed to the injector's intermediate plate, and the inner injector plate and the ribs of the inner chamber and nozzle walls are brazed to the outer walls.

The RD-170 has a smooth start transition to full thrust in over 3 s, using tank pressure feed only. After a fully automatic check of all of the TCs, the TP is brought to full speed. At shutoff, the thrust drops first to 70% for a few seconds, then to 50% for the next 2 s, where it can be held for up to 10 s and is then shutoff in 0.5 s. This gradual shutdown avoids engine damage, which can occur if the coolant flow is stopped too quickly. The first ground tests (1982) were unsatisfactory. A special committee was convened to analyze the problems and a successful ground test was made in 1984. The first flight was in 1985. This LPRE was used on the Energiya SLV and is being used for the Zenit SLV and the U.S. Sealaunch program (ship-based launch platform).

There are several derivative versions of the RD-170 LPRE.[22,26–28] This four-TC model was originally designed for use in the Energiya space launch vehicle. The RD-171 is almost identical, but designed to fit the Russian Zenit SLV and the U.S. Sealaunch applications. There is a single-TC version (RD-191, which has not yet flown) and a two-TC version (RD-180) with a larger nozzle (106:1 area ratio) and a specific impulse of 337.8 s (in vacuum). This last model was developed with inputs and support from P&W, has been licensed to P&W, and was selected for the Lockheed-Martin Atlas III SLV, which first flew in early 2003.

Development of large LPREs with storable propellants began at Energomash in the late 1950s for application in Soviet ballistic missiles.[21,22,26,27] Early versions of these LPREs used nitric acid, but later versions were converted to N_2O_4 (NTO) as the oxidizer. The RD-214 and 216 were two early large LPREs production engines with storable propellants, namely, nitric acid oxidizer with 27% N_2O_4, and kerosene (RD-214) or UDMH (RD-216) as propellants. The RD-214 had a monopropellant hydrogen peroxide GG, and jet vanes for steering. The RD-216 consisted of two RD-215 engines, each with two TCs and one TP with a more advanced bipropellant GG. The unique injector of the RD-216 and the details of some of the injection elements are shown in Fig. 21. The first orbital flight of a SLV version was in March 1962 for the RD214 and August 1964 for the RD-216.

The RD-253 LPRE has a staged combustion cycle, which was proven earlier in other Soviet engines.[22,26,27] It was the first such cycle for Energomash, and the first for a large Soviet engine using storable propellants NTO/UDMH.[21,22,26] Figures 22 and 23 show the engine and its flow sheet. Engines with this staged combustion cycle give 2–8% better performance than with a GG cycle, and this is particularly effective in high-velocity missions. The first staged combustion cycle experimental engine was ground tested by RNII in 1958/1959 and the first one to fly in 1960 (S-1-5400) was developed by the Korolev DB. It flew on the fourth stage of the Molniya SLV.

The first stage of the heavy lift Proton SLV uses six hinge-mounted RD-253 engines, each with an oxidizer-rich preburner.[20,21,26,27] The early version had the TP above the TC, but later versions had a shorter engine with a side-mounted TP and somewhat improved performance. A clever design feature is the annular ejector in the low-pressure oxidizer feed line. It raises the suction pressure at the main NTO pump inlet and alleviates cavitation problems. Several Russian and non-Russian engines have used ejectors, which are simple, but require more energy when compared to more complex booster pumps. Thrust is controlled by regulating the fuel flow to the preburner, and mixture ratio is controlled for the main TC by regulating the fuel flow to the cooling jacket in accordance with the propellants remaining in the tanks. The RD-253 was also one of the first large production engines with chemical gas pressurization of the propellant tanks. One of its two small GG has a fuel-rich mixture, and the other one has an oxidizer-rich gas. Their

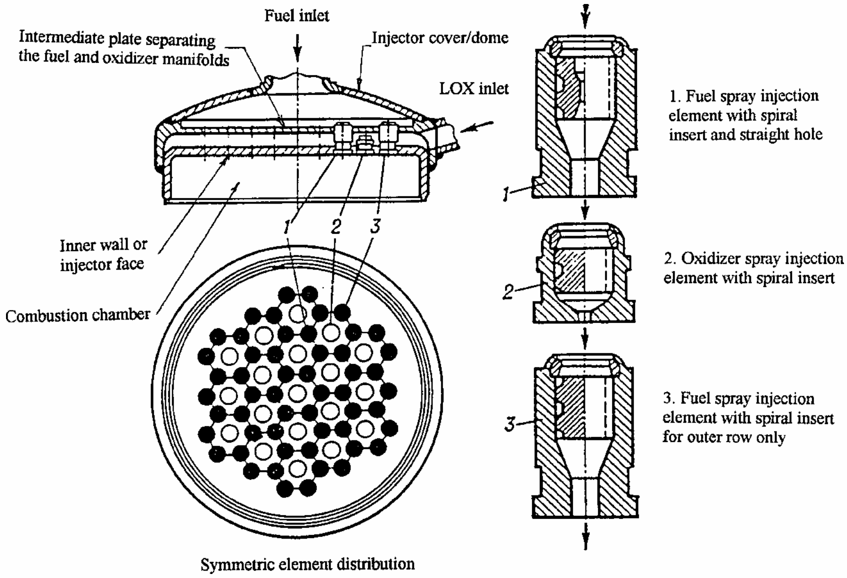


Fig. 21 Injector of the RD-216 LPRE has a mixed, symmetrical orderly pattern of injection elements, enlarged sections on right (courtesy Energomash).

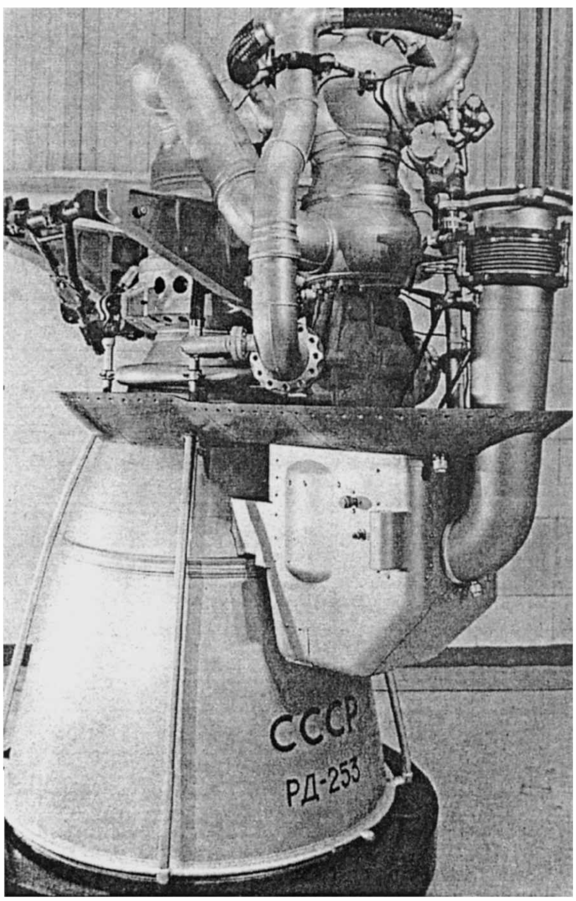


Fig. 22 RD-253 uses storable propellants and is hinge-mounted; this version has the TP next to the TC (courtesy Energomash).

gas temperatures are low enough to not require a heat exchanger for gas cooling.

As a part of the Soviet program to seek higher-energy propellants, Energomash developed between 1969 and 1975 the upper-stage experimental engine RD-301 using liquid cryogenic fluorine as the oxidizer and liquid ammonia as the fuel.[22,26,27,32] This is a historically remarkable and unique achievement because the oxidizer is very energetic, extremely toxic, highly corrosive, and flammable with most materials . It used a TP with a GG cycle, and its high specific impulse of 400 s (in vacuum) was helped by a large nozzle area ratio (108.7:1). It was tested extensively for more than 200,000 s. Other countries (and this author) worked with fluorine as an oxidizer, but at lower thrust and chamber pressure levels, using mostly simple gas pressure feed systems or converted existing small TP-fed engines. The RD-301 is a new pump-fed LPRE specifically designed for this highly toxic oxidizer. The safety and material problems for bearings, seals, valves, and chamber walls were severe, but they were apparently solved. In the United States breathing fluorine is considered a major health hazard in concentrations greater than 1 ppm for relatively short exposures. During 1960 and 1966 Energomash also worked on the pump-fed RD-501 engine using concentrated hydrogen peroxide and pentaborane as propellants.[32] It is the only known development of a pump-fed engine with this very toxic fuel. Although other official reasons were given, the work on both of these engines was most likely stopped because of the potential drastic consequences of an accident with such highly toxic propellants. For the same reason, the work on engines with highly toxic propellants was also discontinued in the United States and other countries.

In 1989 Energomash started the development of two large tripropellant booster engines.[26,28] The RD-701 had two gimbaled TCs, the RD-704 had a single TC, and both used staged combustion cycles. For the initial period of the flight (ascent through atmosphere), the thrust level is high, and the engine would burn mostly LOX/kerosene fuel with a little hydrogen. For the remainder of the flight it burns LH_2 with LOX at a lower thrust. The advantage of this dual-fuel concept is a higher average fuel density, which allows smaller propellant tank volumes, a slightly lower vehicle structural mass, a lower drag, and a slightly improved vehicle performance. The engine had a very high nominal chamber pressure of 4260 psi for its initial operating period. This is one of the highest chamber pressure reported anywhere. Another DB, KB Khimautomatiki worked on other tripropellant engines based on their LOX/LH_2 RD-0120 LPRE. The tripropellant concept was originally investigated and may have been originated by Rudi Beichel (originally of Peenemünde, Germany, and later of Aerojet). The United States and other countries supported studies and a few component tests, but never built the hardware for a complete tripropellant engine. The engine would be more complex and have probably six TPs (including booster TPs) and a more complex TC, and the vehicle performance improvement would be small (estimated at 1–3%). The Russians built three different engines, have done some component and engine testing, and were seeking international partners to share the cost of further engine development, estimated at more than $500 million.

Glushko, like many other rocket designers, unsuccessfully experimented with some novel schemes. For example, he investigated,

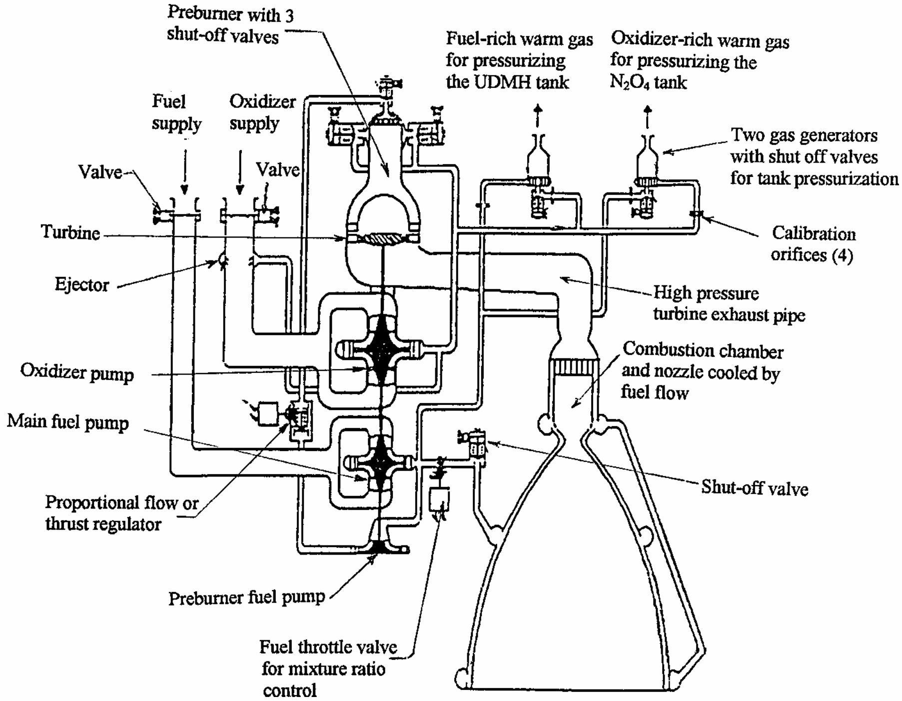


Fig. 23 Simplified flow sheet of the RD-253 with a staged combustion cycle; two small GG provide warm gas for tank pressurization (courtesy Energomash).

but abandoned, a spherical TC. He had the idea to develop a staged combustion cycle with two different preburners, one fuel rich and one oxidizer rich, and he designed and component tested a large engine (RD-270) for it.[32] There would be a gas-to-gas injection into the chamber (no evaporation or atomization of droplets), and it was hoped to give excellent combustion characteristics. The vehicle designers found a larger number of smaller engines more appealing, and this program was never completed. He also experimented with beryllium hydride, a very potent rocket fuel, but an unstable toxic material, and even built an engine for it (RD-560), but the program was not continued.

B. KB KhimAutomatiki or CADB

This was originally the DB of Semyin A. Kosberg (its first chief designer, 1941–1965). Originally the DB worked on auxiliaries for aircraft engines (fuel injection systems, starters) and was started in Moscow. In 1945 it was relocated at Voronezh (about 300-miles south of Moscow) and in 1954 began work on LPREs.[7,9,18–22,33–37] The first job was an aircraft rocket engine using the monopropellant isopropyl nitrate, but this effort resulted in accidents, was not satisfactory, and was abandoned. CADB then developed bipropellant turbopump-fed rocket engines for aircraft starting in 1956, using first LOX/alcohol and then LOX/kerosene. These aircraft LPREs (RD-0100, RD-0101, and RD-0102) were flight tested, but not deployed. The designation KB KhimAutomatiki or Chemical Automatics Design Bureau (CADB) was adopted in 1966.

CADB then developed various good quality upper stage LPREs for guided ballistic missiles and SLVs.[21,22,33,37] Many of these engines used auxiliary vernier TCs, and a number used staged combustion cycles. These upper stage engines have continued to be a key product line for this DB. Table 5 describes selected CADB engines,[9,21,22,33–35] but only a few are discussed here.

The RD-0109 engine (54.8-kN thrust) had a single TC and was used for propelling the orbital stage during the six manned launches of the Vostok program. Flights began in 1960. It launched the first man, Yuri Gargarin, into orbit.

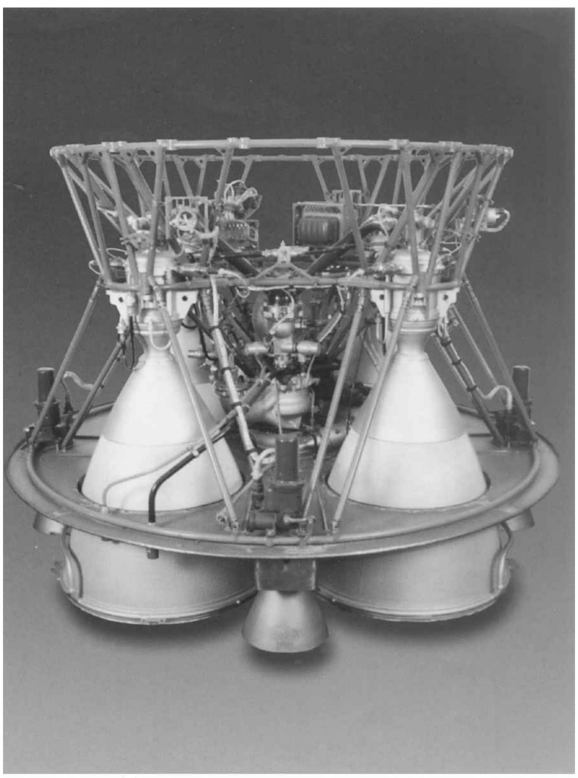
The RD-0110 LOX/kerosene engine is shown in Fig. 24 and its TC in Fig. 25. It replaced the RD-0107 engine on the second stage of the Molniya and Soyuz SLVs, and it first flew in 1964. The RD-0110 uses a GG engine cycle, has four fixed TCs, and a single TP, and its four hinged vernier TCs are supplied with propellants from the main TP.[10,33,35] A solid propellant GG starts the turbine and eight solid propellant igniters start combustion in the eight chambers. The engine has a limited mixture ratio adjustment. Occasional unstable combustion occurred during TC testing, and a program to eliminate the instabilities was initiated. Tests were done with experimental injectors using multiple-injection elements of various designs. This included several types of bipropellant swirling concentric tube-types (where propellant forms conical spray sheets) and injector elements using holes and impinging liquid streams The final injector design was stable during TC operation and had 91 bipropellant injection elements of two types. In the center region, the injector elements are designed for the combustion to begin in the exit cavity of each injection element. In the injection elements near the periphery of the injector, the combustion occurs mostly in the chamber outside of the element. However, occasional instability still happened during the start transient. The solution was to glue six consumable internal fins or baffles to the combustion chamber wall, as seen in Fig. 25. These baffles are made of feltlike porous material that is consumed or burned off in a few seconds. These temporary barriers are a clever unique antivibration device, which are effective only during the start, and are not found in other countries. The RD-0110 TC uses a cooling jacket construction typical of other Soviet TCs. A corrugated intermediate sheet metal is used in the chamber and the upper part of the nozzle (Fig. 13a). All cooling jacket parts are made of stainless steel and are brazed or welded together. Only in the throat region is the inner wall made of a copper alloy with milled channels brazed to an outer stainless steel curved wall (Fig. 13b). Film coolant is injected upstream of the nozzle throat. By 1997, the RD-0110 and its predecessor RD-0107 had propelled upper stages in more than 1200 spacecraft.

CADB developed several LPREs for the second- and third-stage engines of the Proton SLV. All of these engines used NTO/UDMH propellants, had staged combustion cycles, and an oxidizer-rich preburner. The second stage of Proton used four hinge-mounted LPREs, each of which could be deflected by ± 3 deg. Three were the RD-0210 engine and one was a RD-0211 engine, which was very similar, except it also provided the warm gases for propellant tank pressurization.[21,33,35] The oxidizer tank was pressurized by cooled gas, which was tapped off the oxidized-rich preburner, and the fuel

Table 5 Data on selected LPREs of CADB

Designation	Engine cycle	Thrust (SL)/ vacuum (V), kN	Specific impulse s	No. of TCs per engine	Height/ diameter, m	Chamb pressure, MPa	Propellants	Engine mass, kg	Development period	Application
RD-0101	GG	19–39(SL)	240(SL)	1	1/0.4	4.4	LOX/alcohol		1954–1957	E-40A aircraft
RD-0102	GG	15–39 (SL)	250(SL)	1		4.25	LOX/kerosene		1954–1957	Yak-27V aircraft
RD-0105	GG	49.9 (V)	316 (V)	1		4.6	LOX/kerosene		1957–1958	Luna SLV, third stage
RD-0106	GG	294(V)					LOX/kerosene		1958–1960	Second stage, R-9 ICBM
RD-0107	GG	29.4 (V)	324(V)	4			LOX/kerosene		1958–1962	Third stage, Molniya
RD-0109	GG	54.5(V)	323(V)	1	1.57/1.10	5.0	LOX/kerosene	121	1958–1960	Third stage, Vostok SLV
RD-0110	GG	298(V)	326(V)	1 + 4V	1.57/2.40	6.8	LOX/kerosene	408.5	1963–1967	Third stage, Soyuz and Molniya SLVs
RD-0120	SC[a]	1962(V)	455(V)	1	4.55/2.42	21.8	LOX/LH_2	3450	1967–1983	Energiya SLV with four sustainer engines
RD-0124[b]	SC	294(V)	359(V)	4	1.575/2.4	15.5	LOX/kerosene	450	1996–1999	Third stage of improved Soyuz SLVs
RD-0200	GG	6–59(SL)	230(SL)	2		6.7	NTO/UDMH		1957–1961	B-1100 SAM missile
RD-0202[c]	SC	4 × 559(SL)	316(V)	1		14.5	NTO/UDMH		1961–1963	First stage, UR 200 ballistic missile
RD-0212	Consists of	612.6(V)	324(V)	1 + 4V	3.00/3.78	14.7	NTO/UDMH	638	1963–1970	Third stage, Proton SLV
Main RD-0213	SC	581.7(V)	326(V)	1			NTO/UDMH			
Vernier RD-0214	GG	30.9(V)	293(V)	4			NTO/UDMH			
RD-0225	PG[d]	3.92(V)	291(V)	1	1.0/0.45	0.88	NTO/UDMH	23	1966–1971	Almaz orbital station with two engines
RD-0228[e]	SC	1 + 4V					NTO/UDMH		1967–1974	Second stage, RS-20A (SS-18) ICBM
RD-0232[f]	SC								1969–1974	First stage of RS-18 (SS-19) ICBM
RD-0235	SC	Main		1 + 4V			NTO/UDMH		1969–1974	Second stage of RS-18
RD-0236		Vernier		4			NTO/UDMH		1969–1974	or (SS-19) ICBM
RD-0237		Postboost control		1			NTO/UDMH		1969–1974	Third stage or payload maneuver engine
RD-0243[g]	SC/SC	814(estimated)		1 + 4V		27.8	NTO/UDMH		1977–1985	First stage of RSN-54
RD-0255[h]	SC/SC			1 + 4V			NTO/UDMH		1983–1987	Second stage of RS-20 (SS-18-M4) ICBM

[a]Staged combustion. [b]Not yet flown. [c]With three RD-0203 and one RD-0204, which also provides tank pressurization. [d]Pressurized gas feed cycle.
[e]Consists of one main RD-0229 and one vernier engine with four TCs (GG). [f]Consists of three RD-0233 and one RD-0234, which provides for pressurization of propellant tanks.
[g]Submarine missile engine, consists of the RD-0244 main engine, which is submerged in the propellant tank and the RD-0245 Vernier engine with four hinged TCs Fig. 27.
[h]Consists of one RD-0256 main engine and one RD-0257 vernier engine with four TCs; both engines submerged in propellant tanks.



ЖРД РД-0110
RD-0110 LRE

Fig. 24 The RD-0110 has four fixed main TCs, four hinged vernier TCs, a single TP, and a GG (courtesy CADB).

tank by gas from a fuel-rich gas generator and mixer in the RD-0211. This concept of having one of the engines in an engine cluster provide for the chemical tank pressurization is unique and was only found at CADB.

The RD-0212 was used to propel the third stage on a later version of the Proton; it can be seen in Fig. 26. A large U-shaped exhaust duct leads from the turbine to the injector of the main engine. The TP of the vernier engine is not visible in this view. This LPRE consisted of two separate self-sufficient LPREs.[21,22,33,35] The sustainer or main engine RD-0213 has a single TC and is a modification of the RD-0210; both have about the same thrust and specific impulse, except the new engine used a staged combustion cycle. The vernier engine RD-0214 has four vernier TCs 30.9-kN total vernier thrust and a separate small single TP, but it runs on a fuel-rich GG cycle. The vernier TCs can be rotated through a large angle, namely, ±45 deg. Cooled gas, which was bled from the sustainer's oxidizer-rich preburner, was used to pressurize only the oxidizer tank. If oxidizer-rich gas would have been injected into the main fuel tank, there would have been a vigorous combustion in the tank, and the ullage gas temperature would have been excessive. Gas tapped off the fuel-rich GG of the small vernier engine is mixed and cooled and then used to pressurize the fuel tank. The gas temperature is low enough to avoid self-decomposition of the UDMH fuel. This unique combination of a main engine and a separate vernier engine has some advantages over competitive engine designs (simpler R&D and manufacture, possible weight saving, and option to run verniers before or after the main LPRE operation) and has only been observed in Russia. Several of the engines to be discussed have this feature. The author's concept of a likely simplified flow diagram of a typical main engine with an auxiliary, separate vernier engine, and the two tank pressurization schemes is very similar to the diagram of engines used in Soviet submarines, which will be shown later.

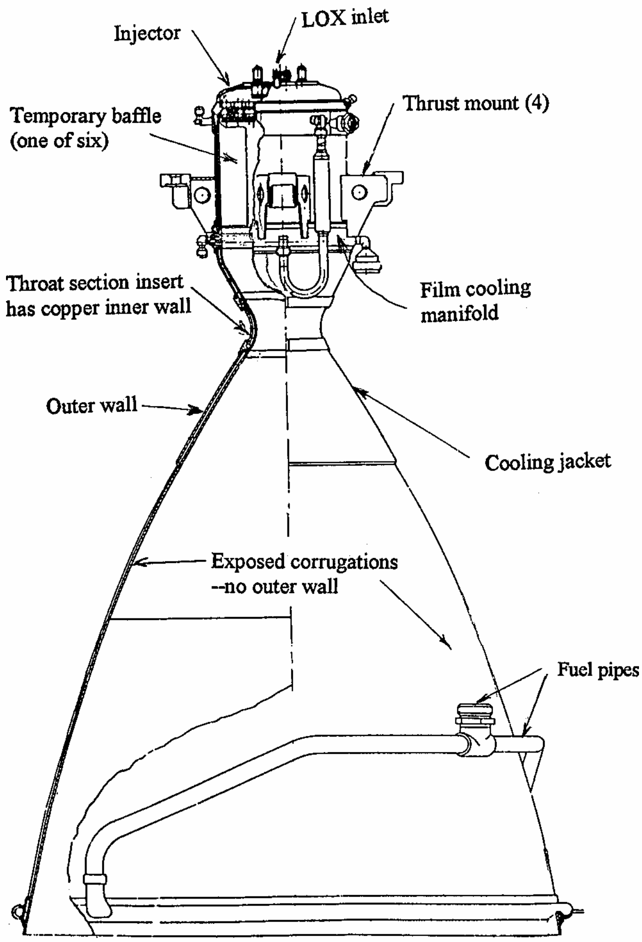
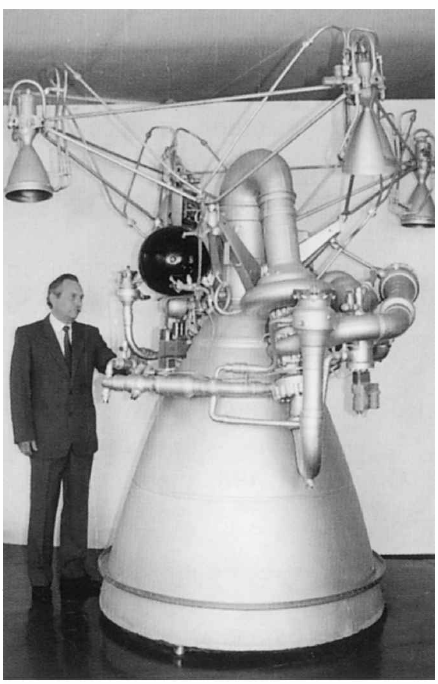
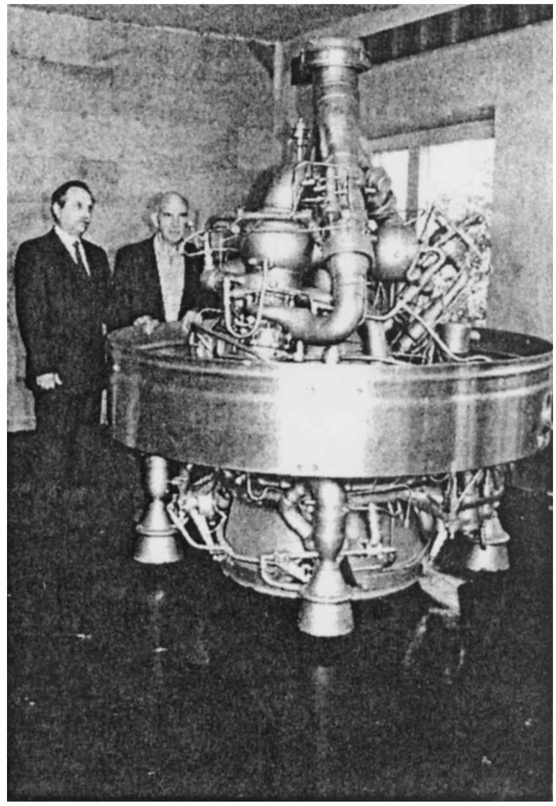


Fig. 25 Partial section of the RD-0110 TC showing one of the temporary antivibration baffles (copied with AIAA permission from Ref. 10 and modified by author).



RD-0212 engine

Fig. 26 RD-0212 LPRE consists of a main engine (RD-213) with a single TC and a vernier engine (RD-0214) with four hinged vernier TCs (courtesy CADB).



RD-0244 single-chamber main engine and the RD-0245 four-chamber vernier engine assembly, used on the first stage of the RSM-54 submarine-launched ballistic missile. (KB Khimavtomatiki)

Fig. 27 RD-0243 LPRE is largely submerged inside the fuel tank of the booster stage of a submarine launched three-stage ICBM (courtesy CADB).

CADB apparently developed only one LPRE (RD-0243) for a submarine-launched ballistic missile (SLBM).[21,22,34,36] However, another DB, KB Khimmash, build more than a dozen others as described in the next section. The RD-0243 engine consists of the RD-0244 booster engine with a single large TC and the RD-0245 vernier engine with four hinge-mounted smaller TCs and is shown in Fig. 27. Relatively large hot-gas pipes, typical of a dual-combustion engine cycle, can be seen to go from the turbopumps to the injectors of the TCs. It drives the first stage of a submarine launched three-stage missile RSM-54, which is an ICBM. The RD-0244 uses an oxidizer-rich preburner, and it includes the pressurization systems for the main oxidizer tank. Its chamber pressure is estimated at 4200 psi, one the highest in the world; in Ref. 18, it is said that it went up to 4600 psi. This high pressure gives a good performance, a relatively small TC, but very high heat transfer and a heavy feed system. The highest chamber pressure of a flying LPRE outside of Russia is only about 3200 psi (space shuttle main engine, block 1).

The upper part of the main engine (RD-0244) was submerged into the bottom propellant (fuel) tank. As will be explained later, this allows more propellant in the missile. The lower part of the propellant tank was sealed to and joined with the diverging section of the nozzle of the TC, and the thrust force was transmitted through the nozzle to the vehicle structure. All of the engine components and joints had to be absolutely leak proof for long periods, while the submarine cruised the ocean with hypergolic propellants loaded into its missiles. The engine flew first in 1987.

The RD-0245 was an accompanying vernier engine with four small movable hinged vernier TCs (seen outside of the propellant tank) to provide flightpath control for this same missile. This vernier engine operated also with a staged combustion cycle, but with a fuel-rich preburner. Cooled gas from this preburner was used to pressurize the fuel tank. The RD-0245 was integrated with and started

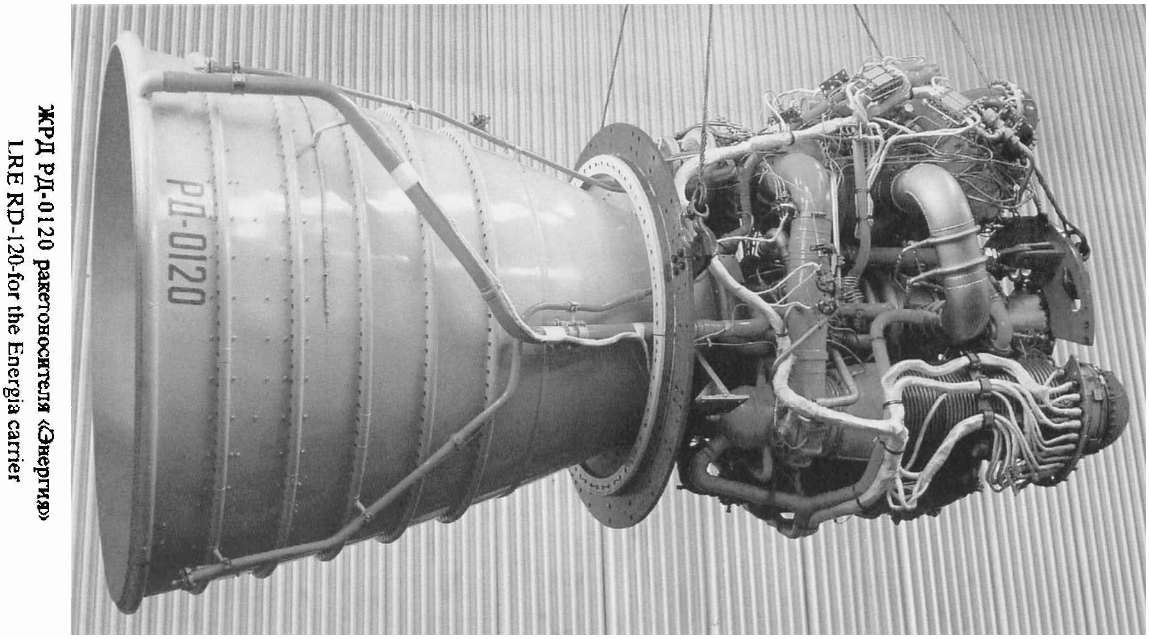


Fig. 28 RD-0120 is the highest thrust LOX/LH_2 engine developed in the Soviet Union[37,38] (courtesy CADB).

simultaneously with the RD-0244 submarine launched booster engine. The flow diagram is similar to that shown subsequently for a dual engine as used in Russian submarines in the next section on KB Khimmash.

In 1983 CADB provided the RD-0255 engine for the second stage of the RS-20 or SS-18 Mod 4 ballistic missile.[33,35] Even though this is not a submarine missile application, this engine was also partially immersed into the propellant tank, which allowed more propellant to be put into a given missile length.

CADB also developed some low-thrust LPREs with pressurized feed systems, NTO and UDMH, for attitude control and limited flight maneuvers.[33,35] An example is the RD-0225, two of which were intended for space maneuvers of the Almaz manned orbital complex. It was designed for 100 starts and 20 min of operating time in space. Another example is the RD-0237 engine used for maneuvers of the postboost payload stage of the RS-18 ballistic missile.

The main exception to the stable of CADB engines is the RD-0120 engine, which uses LOX and LH_2 (Refs. 22 and 33–38). It can be seen in Fig. 28 and as a flow diagram in Fig. 29. Four of these movable (gimbal-mounted) engines were used as the main propulsion of the second stage of the Energiya SLV.[37,38] It had a staged combustion cycle with a fuel-rich preburner. The thrust is the highest with this propellant combination in Russia, and the specific impulse is the highest of any flying Soviet LPRE. The design indicates an advanced state of the art because it benefited from the earlier experimental LOX/LH_2 engines at this and other DBs and from observing foreign LOX/LH_2 engines.

An example of advanced design is the lightweight twin-spool oxygen booster pump, which is shown in Fig. 30. It has two shafts, one inside the other, driving two pump impellers at different rotational speeds, and it is believed to be superior to a single-shaft, two-impeller design.[36] There is no other known TP with two concentric shafts and two pump impellers running at different rotational speeds. The pressure rise in the lower speed booster pump stage allows the second-stage booster pump to be smaller in diameter and lower in weight, and it also allows the main oxidizer pump to run at a higher shaft speed, thus, reducing the size and weight of the main TP. This two-speed TP does the job of suppressing excessive cavitation in any of the oxidizer impellers. The engine's electronic control system is advanced and serves to ensure adequate propellant supply under all transient and steady-state operating conditions. There is a safety system monitoring a series of diagnostic sensors, such as various pressures, valve positions, temperatures, shaft speeds, or axial TP shaft position. The system has special algorithms to evaluate the anomalies of these parameters, and a computer decides what remedy, if any, should be implemented (such as operation at lower thrust or safe shutdown).

The Soviet's first flight with this LOX/LH_2 LPRE was in 1987 in the Energiya SLV, and there has been one other flight (each with four RD-0120 engines) in 1988, before the Energiya program and this engine program were stopped. The first LH_2 engine in the United States started flying in about 1963, the European Space Organization (France) in 1979, People's Republic of China in 1984, and Japan in 1986. The RD-0120 engine was static tested at KB Khimmash, where the static firing test facilities for large LH_2 LPREs are located.

An agreement was reached in the 1990s for Aerojet (United States) to market derivatives of this CADB RD-0120 LOX/LH_2 engine to future U.S. applications, but to date none has materialized. Under a Europe–Russia cooperative agreement on rocket engine demonstrations (initiated by the SNECMA company in France and its Vulcain engine European partners), tests of this CADB RD-0120 engine were conducted in August 1995. The purpose was to validate a mathematical model for future such engines.

In 1995–1996 CADB investigated a tripropellant LPRE based on the RD-0120 LPRE. It is similar in concept to the tripropellant engines undertaken by Energomash as discussed in the preceding section. CADB has ground tested a TC in both the high-thrust tripropellant mode and low-thrust bipropellant mode using an adjustable throat and an injector that can operate with a change in mixture ratio. Further work has stopped.

The RD-0126 is a unique experimental LPRE (LOX/LH_2) with an expander cycle and an expansion–deflection (ED) type nozzle.[33] The program started in 1997, and tests were run in 1998. The experimental ED nozzle of the TC has a cooled centerbody (presumably to put additional heat into the coolant) and an outer nozzle with a special contour to deflect the flow. It is the first such LPRE of a reasonable size in Russia, and its test has been reported to verify the analytical predictions. The merit of ED nozzle is its relatively short nozzle length and its ability to operate at optimum nozzle expansion at all altitudes. Rocketdyne developed and tested two experimental LPREs (up to 50,000 lbf) with ED nozzles in the 1960s and P&W ran an expander cycle engine in the late 1950s.

C. KB Khimmash or Chemical Machinery DB

This design organization was headed by Alexei M. Isayev (see Ref. 39), when it was established in 1943. It was initially a section in another DB, and Isayev was made the chief designer of it in

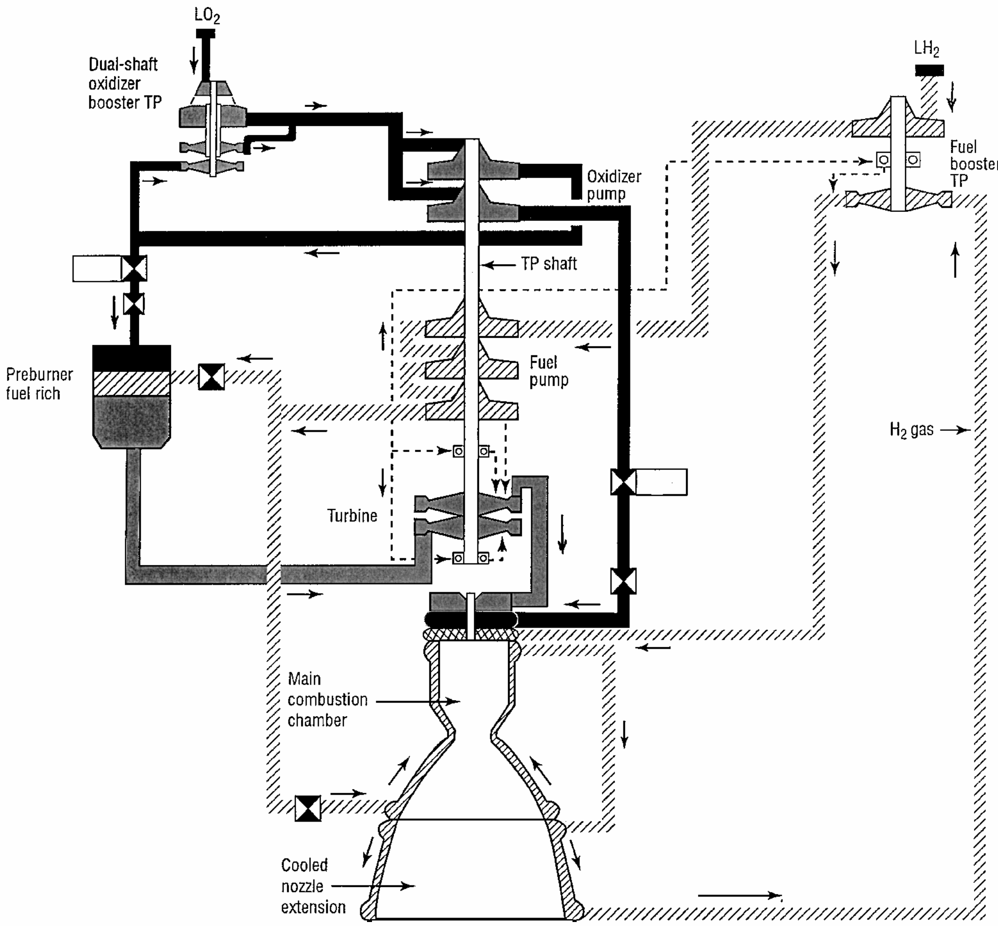


Fig. 29 Simplified flow diagram of the RD-0120 LPRE with a staged combustion cycle engine and booster pumps. Adapted for Ref. 38.

1947. In 1959 it became an independent DB.[7,9,18–22,40] The name KB Khimmash [Chemical Machinery DB (CMDB)] was applied beginning 1967.

Isayev is believed to be the inventor (in 1946) of the brazed cooling jacket design for large thrust chambers. This design, shown in Fig. 13a, has an inner hot sheet metal shell (stressed by uneven thermal expansion and the pressure of the cooling fluid), an outer cool shell, which takes the pressure loads in tension, and the intervening corrugated sheet for forming the channels and connecting the two shells. Isayev is also credited for the submerged engine concept used on submarine-launched multiple-stage missiles as discussed later. In 1950, Isayev is reported to have tried a cruciform cooled injector baffle in a large TC that had combustion instability incidences. This would be the first Soviet baffle, and reportedly it was successful. This idea of curing instabilities with cruciform baffles may have since been used in other Soviet thrust chambers, but this has not been verified. A decade or so later injector baffles were discovered in the United States, but of different design and for much larger TCs.

This DB developed and built 1) aircraft superperformance rocket engines in the 1940s (not discussed in this summary paper); 2) small pulsing thrusters for attitude control and minor maneuvers of spacecraft, satellites, or upper stages; 3) spacecraft maneuver engines between 1957 and 1972 (sometimes with the propellant tanks and even a complete upper vehicle stage) for Earth orbit injection, moon, planet, or deep space missions; 4) LPREs for SLBMs beginning in 1956, and 5) LPREs for tactical missiles in the 1950s.

Beginning in the late 1960s, the development of hydrazine monopropellant and NTO/UDMH bipropellant low-thrust, pulsing engines resulted in a series of available qualified spacecraft engines for flight control in sizes from less that 1 lbf to about 200 lb. There was one that was larger at about 600 lbf. All used gas-pressure feed systems and fast acting valves. They have been used in many Soviet satellites, spacecraft, space stations, missiles, and SLV upper stages for attitude control, station keeping, minor trajectory maneuver corrections, etc. An example is the DOK-10 hydrazine monopropellant engine with a thrust of 10 N (2.2 lbf), a vacuum specific impulse of 229 s, a nozzle area ratio of 46, using an iridium-based solid catalyst, which was heated to enhance fast starting, repeatability, and stability. An example of this DB's product line of bipropellant TCs is the DST-100A, with NTO/UDMH, with a vacuum thrust of 100 N (22 lbf), a specific impulse of 304 s (in vacuum) at an area ratio of 100 to 1. One model reportedly was tested satisfactorily for 450,000 ignitions, which is remarkable.

This Khimmash DB also developed approximately 30 different engines for lunar and planetary flight missions, for apogee and other orbital maneuvers, retrorockets, planetary or moon ascent and descent LPREs.[18,19,22] Figure 31 shows an example; it is the KDU-414 LPRE with nitric acid and UDMH, with a thrust of 1.96 kN (445 lb) and a nitrogen-pressurized feed system. It was developed around 1958–1960 and used for orbit maneuvers in planetary missions (Mars, Venus) of two versions of the Molniya SLV and also with communications satellites. Another example is the lunar soft-landing engine KTDU-417 (1968–1970). It has two restartable TCs, both with variable thrust, a pressurized feed system, and uses nitric acid and UDMH propellants. The larger single unit [7.35–18.25 kN (1650–4100 lbf)] is restartable, runs for 10 or 11 min to slow down the vehicle during descent and was used for the main lunar descent trajectory for the Luna program. The second smaller dual-TC unit runs for up to 30 s just before moon touchdown; its thrust varied from 2.0 to 3.4 kN (456 to 770 lb).

In applications with low thrust, where regenerative cooling is no longer effective (as in some of the thrusters for upper stages and verniers), the Soviets have used in at least one design some ablative thrust chambers using a glass-fiber plastic laminate with a steel outer wall. This is particularly effective with multiple restarts because the fuel, which would be trapped in the cooling jacket, would overheat

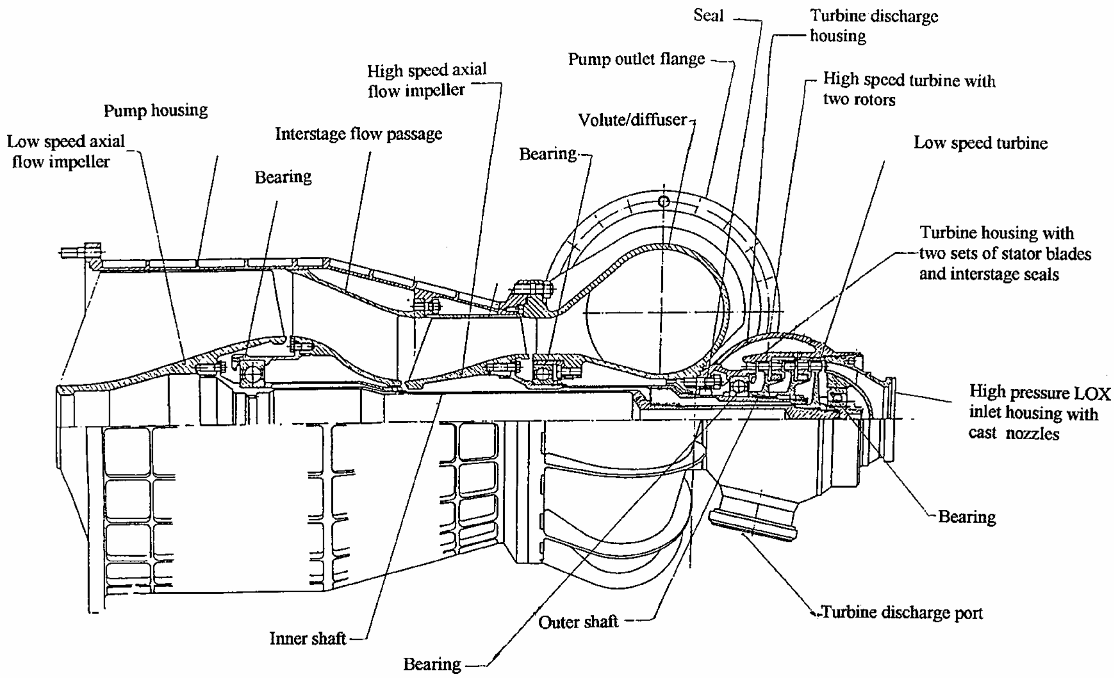


Fig. 30 Oxygen booster pump of the RD-0120 with two shafts, one inside the other, driving two pump impellers at different speeds.[38]

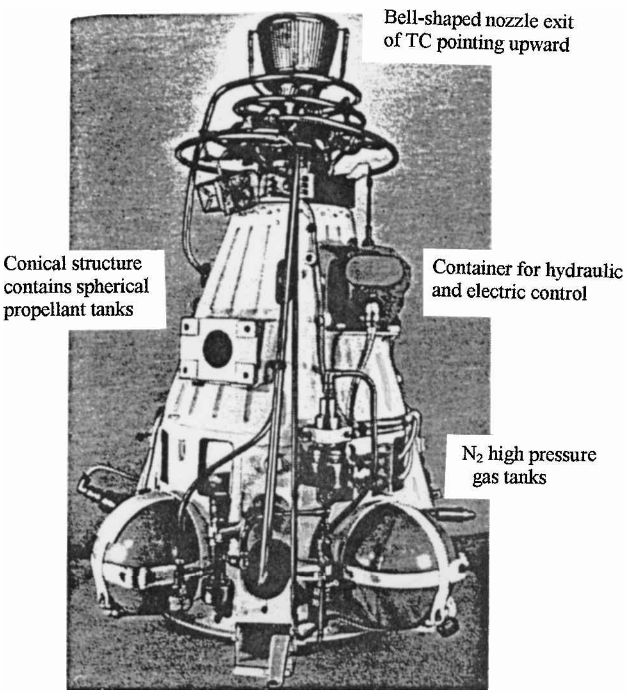


Fig. 31 KDU-414 engine was used for orbit maneuvers of several spacecraft launched by the Molniya SLV.[8]

or decompose due to heat soak-back between pauses in thrust pulses.

The Soviet Union had a number of different submarines capable of carrying and launching ballistic missiles.[21] Some of these SLBMs had solid propellant rocket motors, but historically the majority of these missiles used LPREs with hypergolic storable propellants, namely, NTO/UDMH. They developed single-stage ballistic missiles, two-stage missiles of intermediate ranges, and at least one three-stage missile, which had ICBM range, but a smaller payload. The early missiles with LPREs were single stage and had conventional lightweight propellant tanks with elliptical ends and an intertank structure between tanks. Because the length of a missile carried by a submarine is limited by the height of the submarine, designers used a common single-wall bulkhead between the missile's oxidizer, and the fuel tanks and then they submerged the engines inside one of the propellant tanks. Figure 32 shows a simple diagram comparing these two concepts for a typical two-stage submarine-launched missile. The vehicle's length can be reduced by 20–35%, or alternatively for a given diameter and missile length, the amount of propellant can be increased accordingly. The second-stage LPRE and its movable vernier TCs were placed inside a propellant tank of the first stage. The first-stage LPRE was also submerged with only part of the nozzle exit section protruding out from the tank and the hinge-mounted vernier TCs of the first stage were outside the tank. At stage separation an explosive cord, placed on the propellant tank wall, separated the second stage from the first stage, but a portion of the severed empty tank remained with the upper stage. This design concept resulted in a very compact package and a short missile length, but was achieved at a significant penalty in inert mass and probably at a higher risk of failure.

The first few SLBMs were not designed to withstand the external water pressure and could not be launched under water from a submerged submarine. The submarine had to rise to the surface to launch its missiles. One of the earliest ship-launched missiles was a modification of the R-11 land-based short-range ballistic missile (SRBM).[9,21] The KB Khimmash LPRE for the R-11FM (marine version of the R-11missile) was similar to the land-based version identified as the S.2.253 LPRE. It had about 8 ton of thrust and was originally developed during 1952–1957.

When the dynamics of underwater launch were understood and when the propellant tanks and the LPREs were structurally strengthened, then a submerged launch from a submarine could be undertaken. In most of these submarine-launched missile stages, there are really two LPREs.[9,21] One is for the main propulsion unit, and it usually has a single, fixed TC, a TP, and a staged combustion cycle with an oxidizer-rich preburner. The other is a complete but separate LPRE with four hinged vernier TCs, a small TP, and either a GG or a preburner, which are fuel rich. Figure 33 shows the author's interpretation of a simplified schematic diagram of this dual-engine system. For clarity of presentation, the vernier TP, GG, and gas cooler are shown outside of the vehicle envelope in this two-dimensional diagram. Actually these assemblies should be located between two (of the four) vernier TCs outside of the plane of the paper. The oxidizer tank is pressurized by bleeding oxidizer-rich gas from the preburner

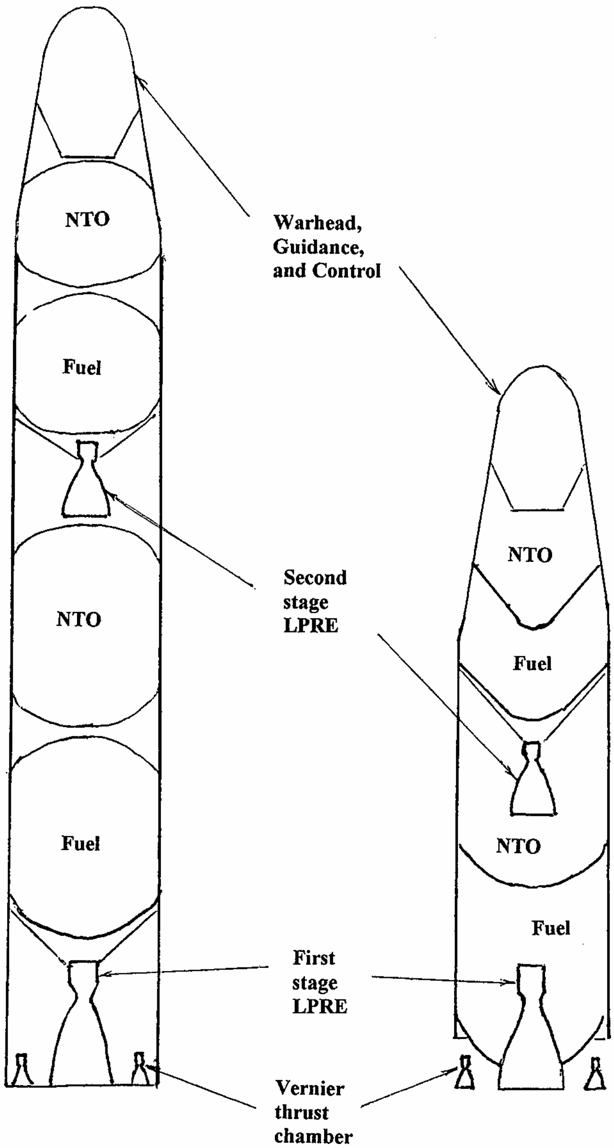


Fig. 32 Comparison of the missile length of two design approaches for propellant tanks inside a missile.

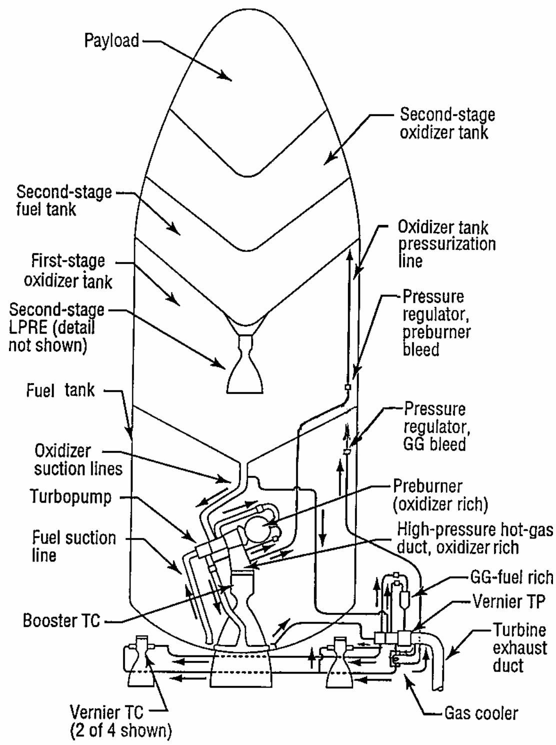


Fig. 33 Author's concept of a simplified flow diagram for a dual engine (main engine and vernier engine) as used in Russian submarines or some of the CADB dual engines.

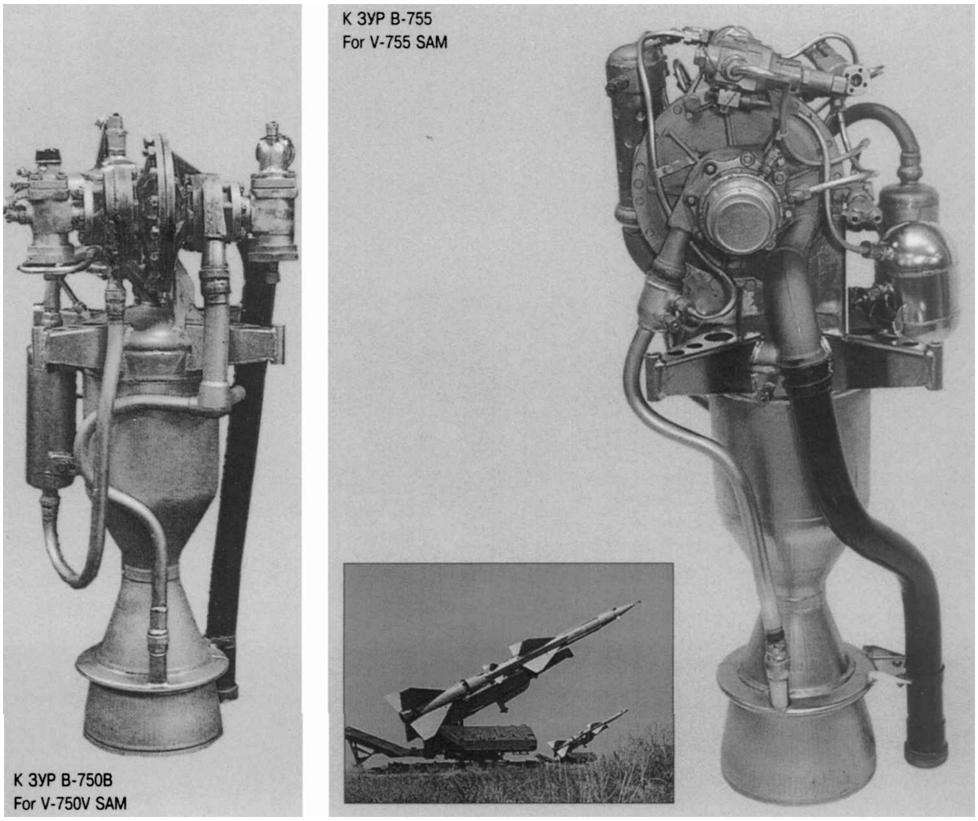
gas at the turbine discharge and cooling the gas in a heat exchanger with propellant. The fuel tank is pressurized by bleeding some of the fuel-rich turbine exhaust gas from the vernier engine TP outlet, cooling it, and piping it into the main fuel tank. Hot-gas pressure regulators control the pressure of the flow to the propellant tanks. A similar flow diagram probably may also apply to the RD-0244 and RD-0245 of CADB described in the preceding section and to some LPREs submerged in the tanks of recent larger military missiles.

One of the problems of pressurizing propellant with hot reaction gases is that the propellant in the tank is heated by the hot gas and by contact with the hot parts of the submerged engine. The last part of the propellant flowing from the tank is the warmest, and this will raise the vapor pressure of the propellant toward the end of the operation and may cause cavitation in the pump. To avoid this problem, the designers used liquid/gas heat exchangers using liquid propellants to cool the tank pressurizing gases from the turbine exhausts, and furthermore, they slowed the TP speed toward the end of the operating duration, which reduces the thrust, but extends the cavitation limit. A novel vortex-type liquid/gas separator (built into the pump) was developed, and it allows any gas to be separated and discarded. This clever concept prevents gas from entering the TC because gas bubbles could initiate combustion instability and could enhance cavitation. Such a gas bubble removal device has not been found elsewhere.

There are many places on a submerged engine where leaks can occur either during storage or during operation, such as at piping joints, valves, welds, injectors, TP seals, GG, flexible joints, vent lines, drain lines, or sensors. Even a small leak of one hypergolic propellant into the other would have disastrous effects on the missile and the submarine. Therefore, an all-welded construction was used, with rigorous inspections and pressure testing during manufacture and special design features to prevent leaks. The hot components, for example, preburner, turbine, or hot-gas ducts, were provided with heat shields to minimize evaporation or decomposition of propellant, which would otherwise be cooked on the hot parts. Visual inspections of the engine or prelaunch engine checkouts were essentially impossible. Ignition probably occurred in the launch tube or just outside of the launch tube of the submerged submarine. This is a class of LPRE that is not known to exist in other countries.

This DB built submarine-launched LPREs for immersion in propellant tanks, but there were no published engine details available. The RD-0243 (actually developed by CADB) in Fig. 27 is the only photograph of such an engine known to the author. When the data from Soviet submarines and missiles[7] are considered, the KB Khimmash probably developed about 15 different LPREs for booster and upper-stage applications in submarine-fired ballistic missiles.

Very little detail was available on the LPREs for surface-to-air missiles (SAMs).[9,21] In the late 1940s, Isayev attempted to improve the German Wasserfall antiaircraft missile by trying chemical tank pressurization, but this effort was abandoned. This DB designed several LPRE for the upper or second stages of several SAMs. The first stage had a solid propellant motor. All LPREs used a pump-feed system and a GG cycle and used nitric acid with 20% N_2O_4 and a hypergolic-amine-based fuel. Reportedly the S.09-29 storable propellant engine of 8-ton thrust was developed around 1950 and installed in the SAM 205/R-113, also known as SAM-1. The S-5-1 engine, also known as K 3YP engine, was developed during the 1954–1958 period. A modified version of this engine was used on the 217 and 218 SAMs (also known as SA-2) and in an uprated version (18 ton) in the 5Ya24 SAM. Two versions of this basic engine are shown in Fig. 34. Figure 34a shows an engine that had 3100 kgf (about 6800 lbf) thrust and that was used on the V-750 SAM. The



a) b)

Fig. 34 Two LPREs for the upper stages of the V750V and V-755 surface-to-air missiles put into mass production.[21]

engine in Fig. 34b could be throttled between 3500 and 2075 kgf (7700 and 4560 lbf) and propelled the second stage of the V-755 air defense missile.

In addition to KB Khimmash, the CADB also developed some LPREs for SAM applications.[21] At least three different SAMs were put into mass production in the 1950s. All had a TP-fed LPRE with a GG and some could be throttled. A version of the SA-2 model was exported to other countries for their air defense. Thousands were installed around Moscow, Leningrad, and other cities. The Soviets were in such a hurry that some of these missiles were deployed before they were fully qualified. As many as 2000–5000 LPREs were built of just one version of this defense missile and one source[9] said the total number of LPREs could have been between 10,000 and 20,000. These were the largest production quantities of pump-fed engines in all of LPRE history.

During the 1958–1962 period, the KB Khimmash DB improved an engine for an up-rated modernized version of an existing short-range surface-to-surface missile. This turbopump-fed engine used nitric acid and kerosene propellants, had about 13.4-ton (about 29,500-lbf) thrust, and used a single TC. Originally, it propelled the mobile R-17 short-range missile. It became the renowned mobile Scud B missile that was exported to various countries including Egypt, Iran, Iraq, Libya, North Korea, Slovakia, and Syria. An up-rated longer range version (more propellant, but less payload) was used by Iraq against Israel and Saudi Arabia in the Desert Storm conflict.

This DB also developed a cryogenic LOX/LH_2 engine (identified as KVD-1) as an alternate for a top stage of the N-1 lunar excursion vehicle during the late 1960s and early 1970s.[40] It used a staged combustion cycle and had about 70-kN thrust. The two verniers TCs of 2 kN each using LOX and gasified hydrogen were part of this system. The N-1 space vehicle program was canceled in 1974, and this engine program was stopped. The engine now seems to have been revived, and it has been designated for use on the fourth stage for one version of the Proton program. One engine version has been demonstrated in ground tests and has been offered to India to serve as an upper stage in their SLV.

D. Other DBs

Two DBs, the Kuznetsov DB (today part of Samara Science and Technical Complex) and Lyulka DB (today part of Saturn Science and Production Association) had been working exclusively on aircraft and turbojet engines, but in the late 1950s they were ordered by the Soviet government to develop rocket engines to support the growing national spaceflight effort. Kuznetsov's DB developed 10 large LPREs (all with LOX/kerosene and staged combustion cycles), and most of these were put into production.[18,19,22,41] Several of these (thrusts between 1500 and 400 kN, vacuum) were flown in the first four stages of the N-1 lunar flight vehicle. There were problems in all the four N-1 launches, and one of the LOX pumps failed in one of the attempted flights. Lyulka developed a LOX/LH_2 engine (renamed D-57) of about 400-kN thrust during the 1960s as a potential alternate upper-stage engine of the N-1, but it has not flown.[40,42] The LPRE efforts at these two DBs were stopped, shortly after the N-1 program was canceled in 1974.

NII Mashinostroyenia specialized in small, reliable bipropellant thrusters using NTO/UDMH and some with refractory metals for attitude control and space maneuvers. Their poducts have flown successfully in more than 800 flights.

The Yuzhnoye DB is located in the Ukraine and part of a vehicle development and production complex.[18,19,21,22] Since 1954, they developed and built LPREs such as vernier engines, satellite control engines with multiple-thrust chambers, at least one postboost control rocket engine system for adjusting the terminal velocity (and, thus, the targeting) of multiple warheads in a missile payload, and some upper-stage engines. They built two LPREs with hot gas side injection into the diverging nozzle section for changing the thrust vector in pitch and yaw. Today they still work closely with or for Russian rocket vehicle organizations.

The Korolev DB (today KKR Energiya) was named after Sergey Pavlovich Korolev, the founder of the Soviet space program, and this DB developed the historic R-7 ICBM and historic early SLVs. Today this DB is still involved with SLVs.[18–22] Their LPREs are really a supplementary product line. It includes at least a dozen LPREs for upper stages, space maneuvers, or flight control. The first engine that flew with a staged combustion cycle in 1960 came from this DB.

VIII. Summary of Key Events, Accomplishments, and General Findings

The LPRE capability in Russia and the former Soviet Union was more extensive and LPRE work was more active than that of any other nation. During 1950–1998, their organizations developed, built, and put into operation a larger number and a larger variety of LPRE designs and vehicle designs than any of the other nations. The Soviets had more liquid propellant ballistic missiles and more SLVs derived or converted from these decommissioned ballistic missiles than any other nation. They also had dedicated SLVs such as the Zenit and Energiya. As of the end of 1998, the Russians (or earlier the Soviet Union) had successfully launched 2573 satellites with LPREs or almost 65% of the world total of 3973 such launches up to that time. A major share of these Russian satellites was presumably for military purposes. In the author's opinion at least 500 different LPREs have been developed. For comparison the United States has developed more than 300.

The timing of several historical flights was earlier in the Soviet Union. This includes the flight of the world's first ICBM (R-7 in 1956). It preceded the U.S. Atlas first ICBM flight by about 5 years. The Soviets launched the world's first satellite (Sputnik, 4 October 1957) and the world's first manned orbiting spacecraft (cosmonaut Y. A. Gargarin, 12 April 1961). It used a modified R-7 ICBM.

The Soviet Union developed in the late 1970s and is still building the RD-170 LPRE, which has the highest thrust (1.77×10^6 lb) in the world. The highest thrust flying U.S. engine, the F-1 at 1.50×10^6 lb, was developed about 15 years earlier.

The Soviets have also developed engines with the highest known chamber pressures. Several of their engines had chamber pressures between 3800 and 4250 psi. The higher chamber pressure allows a higher nozzle area ratio, a somewhat higher performance, and the design of a smaller size nozzle and thrust chamber, which can be easier to package into a flight vehicle. Disadvantages are increases of the heat transfer and a higher inert mass of the engine.

Since 1960, the Soviet Union built and has flown at least 30 LPREs with a high-performance staged-combustion engine cycle. In contrast the United States has flown only one about 20 years later, and the Japanese have flown one such LPRE. Most of these Soviet engines used an oxidizer-rich propellant mixture in the preburner, a feature not found elsewhere. The Soviet LOX/LH_2 engines, the United States and the Japanese LOX/LH_2 engines used a fuel-rich mixture.

The Soviets were the first to develop and use strap-on droppable booster stages with liquid propellant engines and propellant tanks in several of their SLVs and early ICBMs. These were designed and built as a first stage and not as an add-on to increase the payload capacity, as with a number of U.S. solid propellant strap-on boosters.

They were the first to develop a number of engines with four large TCs being fed by a single TP, beginning in the 1950s. This engine is 20–35% shorter than a single chamber engine of the same total thrust and chamber pressure. This reduces flight vehicle length and usually some vehicle structural mass, but a multiple TC cluster is more complex and has a larger diameter or a larger vehicle cross section than a single engine, which leads to a substantially higher vehicle drag. In at least two engines, the designers went to a four-chamber version because they found it to be more difficult to remedy combustion instabilities in the larger single-chamber version. The four TC scheme has been copied by other countries, such as the People's Republic of China and the United Kingdom.

The first piloted LPRE-powered glider flight was in 1940. The glider was towed to altitude by an aircraft, and the LPRE was fired after the glider was released. This was a little earlier than rocket-powered manned glider flights by other nations. The Soviets were the first to fly a piloted experimental aircraft powered solely by a rocket engine. It took off under rocket power and flew first in 1942. Both engines had a gas-pressure feed systems with heavy tanks. The airplanes were too heavy to have a useful flight range. By 1945, they had ground tested a heavy-duty TP-fed, throttling, restartable aircraft superperformance engine, a remarkable accomplishment for this time. The LPRE had a TP, and the propellant tanks were substantially lighter; such an LPRE was flight tested in 1947.

Between 1938 and 1956, about 16 aircraft-type LPREs were developed. Most of these were installed and flight tested in about 12 different experimental military Soviet airplanes for superperformance (where a LPRE augments a jet engine), for rapid climb and fast maneuvers at altitude, and some of these for JATO. One LPRE, the RD-0102, was installed in a group of Yak-27V fighter aircraft of the Soviet Air Force for operational evaluation. None of these aircraft were used in combat. The Soviet aircraft rocket engines were not fully reliable, caused several flight failures and the deaths of several pilots, and were not really accepted by the Soviet Air Force.

The Russians are knowledgeable about liquid propellants. A good number of different liquid propellants have been studied and tried in LPREs. They synthesized and tested a new synthetic kerosene with a higher performance and flew it in a few selected upper stages of SLVs, such as the Proton. With subcooled LOX, this synthetic fuel gave about 20 s more specific impulse than ordinary LOX/kerosene, which substantially increased the payload. They developed engines with methane as a fuel and other engines with liquid fluorine as the oxidizer. In the last 30 years, they seem to have settled on a few specific propellant combinations, each for a specific category of application. They are LOX/kerosene for the LPREs of some SLVs and NTO/UDMH for military applications, upper stages of SLVs, and spacecraft and flight control engines. They also developed good LOX/LH_2 LPREs for upper stages of SLVs and flew one such engine between 1987 and 1988. At the time of this writing, there did not seem to be an active flight program in Russia with this cryogenic propellant combination.

Their TC technology matured early. The first hypergolic ignition was demonstrated in the Soviet Union in about 1935; in Germany it was also 1935, and in the United States it was 1940. The Soviets had partially cooled TCs (by fuel in the nozzle region only) as early as 1933 and 1934. The first fully regeneratively cooled TC dates back to about 1937. The Germans did it around 1935 or 1936, and the American Rocket Society tested one in 1938. As described in Sec. VII they developed and refined a clever cooling jacket design with a corrugated intermediate sheet metal that is unique to the Soviet LPREs. The Soviets had excellent tooling for fabricating complex cooling jackets and injector configurations with three-dimensional contours using relatively thin specialized metal alloy plates, sophisticated welding methods, and high-temperature brazing techniques. This TC cooling jacket construction is usually lighter than other types. Good combustion efficiencies and good efficiencies for converting the energy of the hot, high-pressure gases into the kinetic energy of the nozzle exhaust flow were demonstrated early.

High-frequency combustion vibrations have occurred during the development of a good number of Soviet large LPREs starting in the 1940s, and these instabilities have delayed their schedules and changed several of their engine development projects. A major multiyear analytical and experimental effort, which involved several organizations, has helped to gain a better understanding of this complex phenomena and has lead to several methods that were successful in eliminating this destructive gas-pressure oscillation in specific LPREs. A unique solution were the temporary consumable baffles, that control certain combustion vibrations during the start transient.

The USSR was the only country known to put LPREs into submarine launched ballistic missiles. About 15 different LPREs (with hypergolic storable propellants) were developed for single stage, two stage, or three stage SLBMs. These engines were immersed in hypergolic propellant inside a propellant tank, while the submarine cruised the oceans for long periods. These LPREs were leak-proof, had essentially no prelaunch check out, and could be started quickly. Their novel engine and propellant tank design allowed a substantial reduction (up to about 35%) in missile length, which made it possible to put powerful multistage missiles into submarines. This submerged engine technology is unique and has also been applied to at least one of the upper stages of a ground-launched Russian ballistic missile.

In the area of TP technology the Soviets made some technical contributions. For high chamber pressure LPRE operations it was necessary to develop TPs with pump discharge pressures of 600 kg/cm^2 (almost 9000 psi) or more, which is the highest of any known TPs. While high pressure TPs were developed in the USA, they were not integrated into an engine and they did not fly. The first simple Soviet turbopump (intended for aircraft rocket engines) was statically tested in 1945, before they knew about the German World War II developments. In 1945 they learned about the two in-line shafts concept of the German V-2 TP. In the 1950s the Soviets designed a number of TPs for some of their early large LPREs with this inline two-shaft concept. Compared to an equivalent single-shaft TP concept; this allowed smaller, lighter shafts, more durable, smaller bearings, and sometimes a lighter TP inert mass, but it resulted in longer and more complex TP assemblies. Most of the TPs developed outside the Soviet Union and many in the Soviet Union had a single shaft design concept. The Soviet Union gets the credit for developing the most powerful TP (250,000 hp for the RD-170). They also developed a novel lightweight booster TP with two concentric hollow shafts (one inside the other) driving two different pump impellers, each rotating at a different shaft speed. This improved the cavitation resistance and may have slightly reduced the booster and main TP masses, but it is more complex and more expensive. None of the booster TP designs of other countries are known to use these dual concentric shaft features. They were early users of axial flow inducer impellers (a concept obtained from the Germans), which reduced the required propellant tank pressure.

The world's largest production of TP-fed LPREs was for the second stages of several defensive antiaircraft missiles during the 1950s. They were deployed in large numbers to defend Soviet cities. Several different LPREs were produced in quantities between 1000 and 5000 each and put into SAMs.

The Soviets (and the United States) produced and flew LPREs with most of the known common designs for thrust vector control (TVC). They put into production TCs with jet vanes (on a few early LPREs only), hinges (rotation about a single axis), and gimbals (rotation about two axes). They also used hinged or gimballed nozzles for the turbine exhaust gas discharge to achieve flightpath control. The most common TVC system for large Soviets LPREs used multiple smaller hinged auxiliary or vernier TCs, which were placed next to one or more large fixed main TCs. The vernier TCs typically provided about 10–18% of the total thrust. In the earlier LPREs, the vernier TCs were supplied with propellants from the main engine's TPs. In some of their more recent LPREs, the vernier TC propellants were supplied from a separate small TP feed system. In effect, it was a separate small LPRE typically with four small vernier TCs and its own GG (or preburner); the propellants came from the same propellant tanks that also supplied the main engines. In the non-Soviet world, the verniers or the reaction control systems usually have a lower thrust (1–5% of total thrust), and usually the verniers were supplied from separate heavy gas-pressurized feed systems. The Soviet Union was the only nation to implement a unique TVC scheme on the RD-857 engine of Yuzhnoye with "warm gas side injection" (tapped off the preburner) squirted into the sides of the diverging nozzle section of a thrust chamber. In the United States, a unique "liquid propellant side injection" scheme was produced in quantity, but none of these liquid injection schemes were found in the Soviet LPRE inventory.

The early investigators in Russia knew about the performance benefits (about 1–3%) of a curved or bell-shaped nozzle exit section in the 1930s and implemented curved nozzles in large LPREs in the early 1950s, about 6 or 8 years earlier than in any other country. The Soviets have, according to the author's available information, not as yet flown an extendible exhaust nozzle, although they ground tested the concept in the 1970s (D-57 of Lyulka) and later on another engine. In the United States, extendible nozzle configurations were flown with solid propellant rocket motors in the 1980s and with a LPRE beginning in the 1990s.

The Soviets put a large number of TCs into the base of several of their launch vehicles and managed to start them all essentially at the same time. The R-7 ballistic missile and its space-launch versions, the Vostok, Molniya, or Soyuz SLVs, each had 20 larger TCs with an additional 12 vernier TCs (total of 32 nozzles in the cluster). There was an engine with four TCs in the vehicle's core and also in each of the four strap-on liquid propellant boosters. The N-1, the largest SLV, had 30 large LPREs in its first stage. Outside of the Soviet Union, the largest number of large LPREs was in the U.S. Saturn I booster with eight large H-1 LPREs and the eight nozzles on the U.K. Black Knight.

Several of the DBs developed a unique engine system consisting of a main larger engine and a separate pump-fed vernier engine, typically with four smaller TCs. There are some advantages in this development and fabrication, and it allows the vernier LPRE to operate before, during, and/or after the main engine operation. Such a system does not seem to exist elsewhere. Also one of the DBs has another unique system, where three of the engines in a cluster of four are alike, but the fourth has provisions to create warm gases for pressurizing the common propellant tanks.

In Russia, the LPRE field is today essentially mature. The basic engine system and key components had been fairly well defined about 40–50 years ago, and reliable operations have been achieved by their LPREs perhaps 30–40 years ago. Certainly there have been new ideas, such as "green" or environmentally more compatible propellants or better materials of construction. These and some other good ideas are still improving LPREs. However, the opportunities for developing a new LPRE are today not as plentiful in Russia as they used to be.

The Soviet LPRE organizations had relatively steady support and funding due to high military or spaceflight priorities, while many other countries had more frequent changes in their annual budgets for LPREs. In part, this relatively steady funding has allowed a steady development of new engine concepts and new LPRE manufacture methods.

In retrospect, a fair part of the LPRE effort was inefficient, particularly during the busy period of the 1960s and 1970s. The cancellation and duplication of major programs caused a poor utilization of LPRE resources. The Soviet Union developed engines and put some of them into production, when they later were really not needed. For example, on urgent military requirements, the Soviets would support two competing engine development programs. They would then select one set of the engines for the intended application. The engine programs that were not selected, were then canceled. Thus, they ended up with quite a number of perfectly good engines that had to be scrapped or put into storage for a possible future application. This duplication helped them sometimes to pick a somewhat better engine, but it was a luxury that other nations could not afford very often. For the heavy N-1 SLV for lunar and planetary missions, they actually fully developed and placed into production at least two engines for every one of the six stages of the vehicle. Furthermore, they also developed several higher performance (LOX/LH_2) upper-stage alternate engines for a subsequent improved vehicle capability aimed at more ambitious missions of the same launch vehicle. When the big N-1 program experienced four successive flight failures and when the U.S. astronauts got to the moon before the Soviets did, the program was canceled. The Soviet Union then had more than a dozen newly qualified engines that did not have an application and had to be scrapped or put into storage for a potential future application.

Many of the flight applications, for which LPRE have done well, are today obsolete. For example, Russia no longer uses LPREs for JATO, aircraft superperformance, or sounding rocket vehicles. The emphasis in Russia has shifted. The emphasis today is on applications for SLVs, spacecraft, or reaction control for the steering of vehicles. It is not known if there are some new LPREs for as yet undisclosed military applications.

This author looked, but could not find, much information accessible to people outside of Russia on a substantial number of LPREs.

This includes information on old LPREs, on engines developed by certain DBs, LPREs for submarine-launched missiles (with the exception of the RD-0243, where a photograph and a little data were found), very little on postboost control systems for multiple warheads, or data for certain LPRE for military applications. Details of the remedies or analysis for overcoming and remedying combustion vibrations are fragmentary, and almost nothing could be found about critical high-temperature materials or manufacturing processes. The history of Russian engines in this paper is, therefore, based on partial information only and would be altered when the missing data become available.

The LPRE business in the Soviet Union saw its peak from the late 1950s to the early 1980s. This was the period when the staff of the LPRE DBs and the output or deliveries were at their highest. Although the volume of business has greatly diminished, there is today still a lot of activity. This decrease has caused some of the DBs to be directed to leave the field of LPREs. There are fewer Russian DBs engaged with LPRE today. Energomash and CADB have about half as many people now as they used to have.

It appears that the Russians have successfully preserved the LPRE capability and for the time being have maintained this capability in several of the current DBs. They have initiated programs to slowly replace existing engines with newer more up-to-date LPREs. There may be a question if some of these are really needed. Furthermore, some of these DBs have started conversion efforts in other (non-LPRE) technical areas, such as commercial pumps, oil field equipment, or medical devices. In the last decade, the Russians have instituted a policy of exporting LPRE technology and some of their engines. This has also helped to maintain the capability and to obtain some additional funding. More than one DB can at the time of this writing develop any kind of LPRE that may be needed. With the retirement of skilled personnel, it is unknown how long Russia will be able to maintain this capability.

More people were injured or killed in failures of Soviet LPREs or in liquid propellant spills than in all of the other countries. Some were failures at test or launch facilities, failures of experimental LPREs in aircraft, and major accidients, explosions, or spills of hazardous propellants. About 30 years ago the U.S.S.R. government surpressed the news about a major launch accident at Baikonur Cosmodrome Launch Complex (Tyuratam), where 124 people were killed including some high ranking officials. About 30 min before the launch, the second-stage engines of a new experimental fully loaded two-stage long-range missile (R-16) began to fire. The missile broke apart, and the propellants of the first and the second stage spilled, burned, and exploded. Apparently the control system did not have a protective circuit to prevent a spurious electric current from generating an unexpected start signal. Although this failure was not directly the fault of the two LPRE control systems, the resulting disaster involved the sudden spill of tons of toxic, hypergolic HNO_3/UDMH propellants. One of the victims was Marshall Mitrofan I. Nedelin, a former Deputy Minister of Defense and the Commander of the Strategic Missile Forces. A news release falsely attributed his death to an airplane accident.

The Soviet Union exported or provided more LPRE-driven missiles to other countries, than any other nation. They exported defensive missiles (such as the SA-2) and SRBM (Scud) to their allies and to countries they considered to be friendly to them. They offered a LOX/LH_2 engine to India and sold LOX/kerosene engines to the United States.

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