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EXPERIMENTAL RESEARCH AND DESIGN PLANNING IN THE FIELD OF LIQUID-PROPELLANT ROCKET ENGINES CONDUCTED BETWEEN 1934-1944 BY THE FOLLOWERS OF F. A. TSANDER+

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This report describes Soviet research and design planning of liquid propellant rocket engines (hereafter termed LPREs), a field often insufficiently elucidated in the technical literature of the history of rocket technology. The author, a pupil of F. A. Tsander, took a direct part in fulfilling this research in a subdivision of the Jet Propulsion Research Institute (RNII) on a GIRD team headed by Tsander. This report, however, covers only some parts of the history of the development of Soviet LPREs and does not touch upon the research fulfilled in this same period by specialists in other areas of RNII, or in other organizations.

Before moving to the basic topic, I consider it necessary to make a few preliminary observations about the principle characteristics of Tsander's practical work in LPREs insofar as these characteristics have been overlooked in the writings devoted to his work. The name of Tsander is well known in the USSR and abroad as a follower of K. E. Tsiolkovsky and as a great scientist in the field of interplanetary flight theory. He is also known as one of the first research engineers to lay down the foundations for design work on LPREs in the Soviet Union and create the methods for LPRE engineering calculations, projections, and experimental elaborations. His ideas and scientific legacy are thus highly valued in our country and have become the subject of investigation by specialists and historians of rocket technology.

The first conference devoted to the elaboration of Tsander's scientific legacy and the development of his ideas was held in May 1970 in Riga; lectures given by specialists in different sessions investigated his work and clearly demonstrated its importance in the theory and construction of jet engines, in astrodynamics, in life

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+Presented at the Fifth History Symposium of the International Academy of Astronautics, Brussels, Belgium, September 1971.

++A collaborator of F. A. Tsander and a contemporary of Sergey Korolev, Dushkin specialized in rocket engine design and the development during the 1930s and 1940s in GIRD, RNII, and other scientific institutes.

support systems, and also, the influence of his thoughts and ideas in solving the contemporary scientific-technical problems related to rocket engines and cosmonautics.

Being a theoretician and a space flight enthusiast, Tsander attached paramount importance to questions of the choice of method and the direction and sequence of design work—especially as it related to the problems of LPRE. He imbued these questions with a sense of technical reality and scientific validity and perspective. We know that he created his school in the field of the theory and planning of jet engines on the basis of his own theoretical and practical work. The characteristics of this school, as related to LPRE, appears in detailed examination of his theory of rocket engines,[4] methods of propellant calculations, experimental research on the laboratory model "OR-1,"[2] design decisions in applied oxygen LPREs—developed in the GRID engines "OR-2" and "0-10"[3]—and also in the studying of schematics and technical data on LPRE developed by Tsander that formed the tasks undertaken in GIRD.

The following points reflect the basic elements of the idea content of this school of thought in LPRE:

1. Strict scientific and technical substantiation of the data for proposed engines,
2. Introduction of experimental research on models and laboratory devices.
3. Application in the LPREs of propellants based on liquid oxygen, liquified gases, and metals,
4. Implementing construction of LPREs as independent hardware, especially in supply, direction, and regulation of the propellant flow,
5. Development of a one-chambered LPRE allowing an increase in thrust regulated over a wide range,
6. Creation of combination rocket engines which united in one power plant various kinds of engines,
7. Technological efficiency, reliability and power increase in the most advanced designs based on subsystem arrangements for ease of dismantling and substitution, during the development of prototype and final construction stages.

The experience realized in the work at GIRD between 1932-1933 strengthened the belief in the validity of the Tsander school, and in the necessity of developing its methods for application to further activity. After Tsander's death in 1933, his school continued to develop and exerted a significant influence on the work in the LPRE field in RNII—created at the end of 1933—in which his students, followers, and supporters elaborated upon the theoretical, experimental, and design directions pioneered by Tsander. In RNII between 1934-1944, reflecting this stage of Soviet rocket engine development, his followers carried out a widespread LPRE research and development program.

In order to give you an idea of the main directions of this work and the results obtained, I have provided below the basic technical data, construction designs, photographs of some of the devices taken from their original sources (preserved in the archives), in the chronological order of their completion.[1-16]

ALCOHOL-OXYGEN LPRE, SINGLE-FIRING "12-K" ENGINE WITH A THRUST OF 300 kg

This engine, designed, constructed, and tested on a stand in 1935-1936, was earmarked for use in wingless and winged rockets. The distinctive features of the "12-K" engine in comparison with other engines created in GIRD were: a higher level of thrust, and pressure in the combustion chamber, as well as a design construction characterized by vortex mixing of propellants, and the use of ceramic fire-proofed materials of aluminum oxide and magnesium oxide for thermal protection of the chamber and nozzle, without the use of external cooling. The "12-K" engine design is presented in Figure 1. The engine's performance parameters were:[4]

1. Thrust . . . . 300 kg.
2. Pressure inside the chamber . . . . 15 atm.
3. Specific impulse . . . . 210 sec.
4. Pressure of fuel feed . . . . 25 atm.
5. Diameter of sections of the nozzle . . . . 42/82 mm.
6. Volume of the combustion chamber . . . . 2 L.
7. Overall dimensions . . . . 450 x 220 mm.
8. Weight . . . . 13.5 kg.
9. Duration of a single firing . . . . 60 sec.

While testing the "12-K" engine, data was obtained close to original calculations. The engine demonstrated a high stability of burning without pulsation of pressure inside the chamber. Therefore, in 1937 the "12-K" engine was placed in the stratosphere rocket sonde "Aviavnito." The first launching took place on April 6, 1936, and was described in Pravda (April 8, 1936); the second and more successful launching on August 15, 1937, employed a 48-meter launching mast.+ The "Aviavnito" had a starting weight of 100 kg, a diameter of 300 mm, and a length of 3,000 mm. With a load of 32 kg of propellants, the rocket's calculated peak altitude was estimated at 10,800 meters. An overall view of the rocket, installed on the launch stand for the second flight, appears in Figure 2.

+See Mikhail M. Tikhonravov and V. P. Zaytsev, "On the History of the Stratospheric Rocket Sonde in the USSR, 1933-1946," in this volume--Ed.

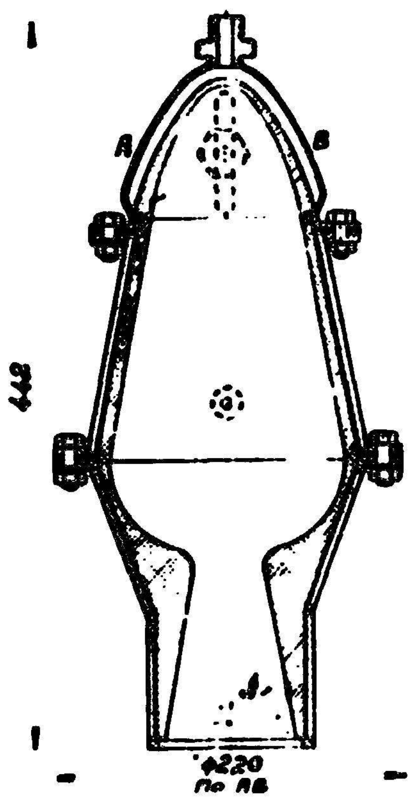


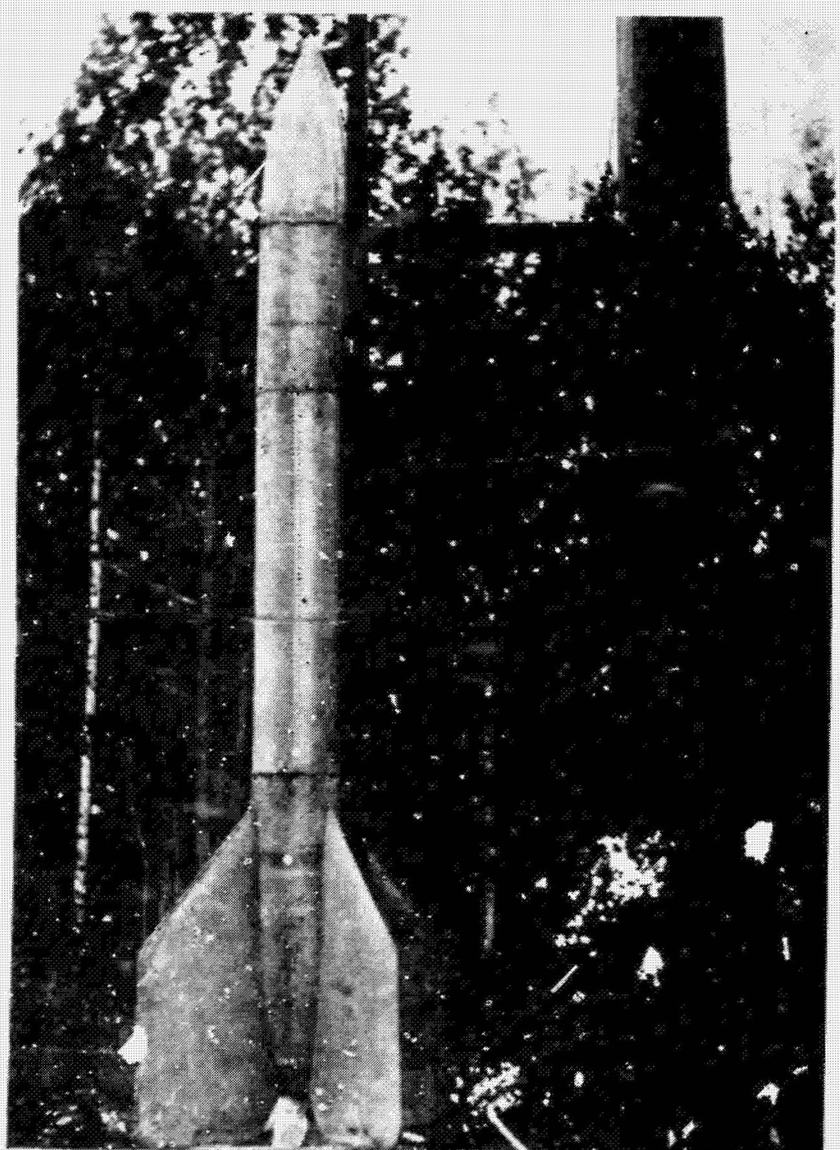
Fig. 1
Schematic of the 12-K Alcohol-Kerosene LPRE

In 1937-1938 research began with the aim of improving the scientific basis of the LPRE engine designs before final construction, to increase the reliability, and to improve the characteristics of recently created models of LPRE working on nitric acid and kerosene. The base for conducting the research was the LPRE Engine Laboratory (at this time part RNII), which was called upon to conduct research on oxygen[5] and nitric acid LPRE, permitted testing of these laboratory models, and propellant combustion tests.[6,7]

Because this research had an applied character, the goal involved studying the more "critical" problems encountered in creating nitric acid LPREs, related to assuring the reliability of the ignition, the stable and complete combustion of propellants during the burning process, and the efficient cooling of the chamber, etc. The initial input and the test results of this research were as follows:

Researching the Processes of Igniting Propellants

The installation consisted of a combustion chamber with a constant volume, with a nozzle and a system for pressure impulse feeding of propellants through atomizers in an



of the propellants into the chamber, etc. Also, the period of ignition delay was established as well as the duration of propellant combustion. The resultant recommendations for starting the nitric acid LPREs provided for the dosage of fuel at the moment of ignition, of the expenditure and mixture ratio of propellant components, and the implementation of ignition and the burning process by controlling propellant flow, made possible in future efforts to increase the reliability of operation of the LPRE.

Researching Combustion and Cooling Processes in the LPRE Unit

This research was conducted on a laboratory model of the nitric acid LPRE unit with a thrust range between 30 and 80 kg and a corresponding pressure in the chamber between 7- and 25 atmospheres. The water-cooled model had sets of interchangeable nozzles, cylindrical parts of the combustion unit, and of centrifuge atomizers for the fuel and oxidizer. Modification of these elements allowed for "modeling" the various cycles of firing and for determining the influence of the different elements on the duration of the firing and its performance characteristics.

The data received from this research provided a clear picture of the phenomena accompanying the firing of nitric acid LPREs, and allowed the formulation of a series of recommendations for future planning. Among the most important were the following propositions:

1. To obtain steady burning and a high completion of combustion, it was necessary to feed the propellants through suitable injectors that assurred the formation of a stable front of flame in a cross-section of the chamber.
2. To obtain reliable external cooling of the combustion chamber and of the nozzle using propellant components, it was necessary to provide variation of the flow in the cooling channels around the surfaces according to the changes in the thermal conditions of the walls of the combustion chamber and the nozzle.

These findings made possible the construction of nitric acid LPREs of a more advanced design, with a corresponding improvement in the reliability of their firing.

THE NITRIC ACID LPRE, MULTIPLE-FIRING "RDA-1-150," FOR THE ROCKET GLIDER "RP-318"

The "RDA-1-150" engine was conceived and developed during 1938-1939 using the basic results of the scientific research described above and the experience accumulated in work on the nitric acid LPRE at RNII earlier. It was designated for use in the rocket glider "RP-318." The design of the "RDA-1-150" engine is presented in Figure 3. Engine performance was characterized by the following data:[8]

1. Propellants . . . . nitric acid and kerosene
2. Thrust regulated in the range of . . . . 50/150 kg.
3. Pressure in the chamber . . . . 8/18 atms.

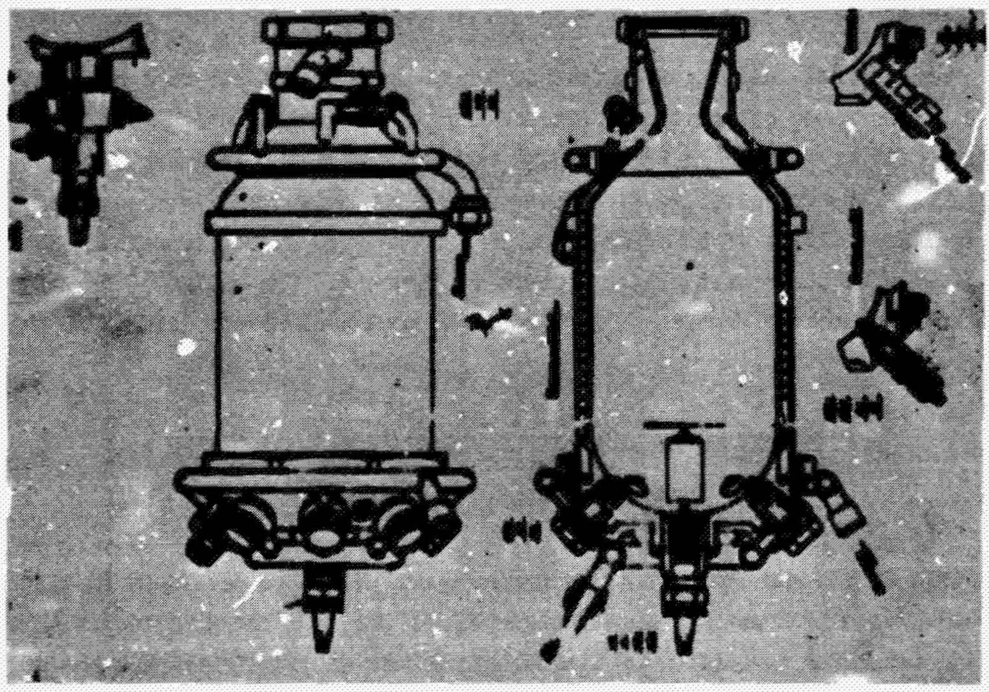


Fig. 3
Schematic of the RDA-1-150 Nitric Acid and Kerosene Engine
for the Rocket Glider "RP-318"

4.	Specific impulse	150/198 sec.
5.	Pressure of fuel feed	13/35 atms.
6.	Diameter of sections of the nozzle	25.5/50 mm.
7.	Volume of the chamber	2.2 L.
8.	Overall dimensions.	420 x 200 mm.
9.	Weight of the chamber (or unit)	10.5 kg.
10.	Duration of an uninterrupted firing	200 sec.
11.	Operating lifetime	28 min.

The features of the "RDA-1-150" design that distinguished it from earlier RNII nitric acid LPREs were the following:[9]

1. Mixing of propellants in the combustion chamber by means of injectors.
2. Engine cooling with two propellant components· the nozzle with kerosene and the cylindrical combustion chamber with nitric acid, with their circulation along spiral canals at changing rates of flow,
3. Thermal protection of the injector plate of the chamber by internal cooling,
4. Dual-stage ignition with the application of an electrical spark and propellant flow controls,

5. A modular design composed of three principal components: the head, the chamber, and the nozzle.

During final tests, the engine performed close to the pre-test calculations. The engine demonstrated stability and reliability during burning which guaranteed its admittance to flight testing in the "RP-318" rocket glider. On February 28, 1940, this rocket glider, with test pilot V. P. Fedorov at the controls, was flown successfully.[10] This was the first flight of a Soviet pilot in a rocket-propelled aircraft.

A view of the rocket glider appears in Figure 4. The design of the "RDA-1-150" engine became a prototype for other, more powerful models of nitric acid LPREs that we built later.

ALCOHOL-OXYGEN LPRE, MULTIPLE FIRING "RDK-1-150," WITH A REGULATED THRUST OF 70-160 kg

This engine and its test stand firing procedures were developed in 1939-1940. This alcohol-oxygen LPRE was likewise designated for use in a rocket glider with the goal of compiling tests for comparison of its technical data and qualities with the nitric acid engine. It was therefore calculated that this engine would perform with characteristics similar to those of the nitric acid LPRE "RDA-1-150" in the rocket glider "RP-318". The design schematic of the "RDK-1-150" engine is presented in Figure 5.

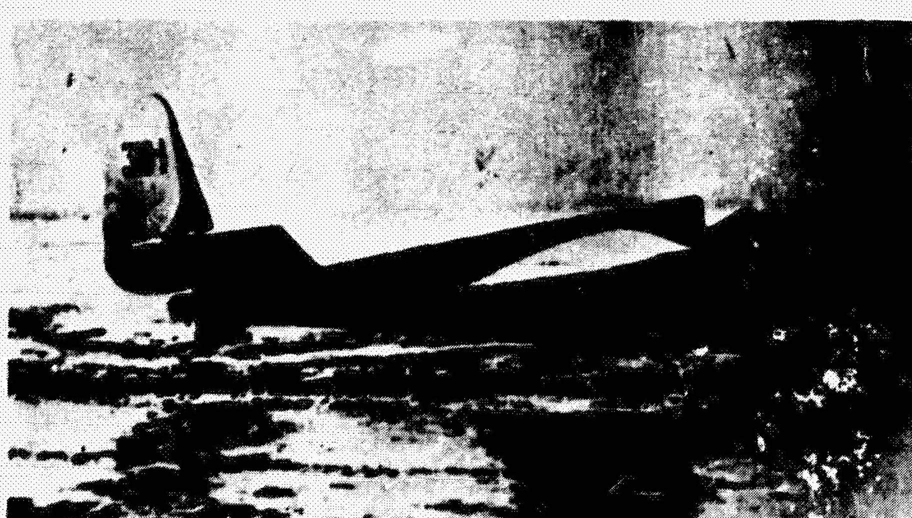


Fig. 4
View of the "RP-318" with the RDA-1-150 Engine Before the First Flight on February 28, 1940

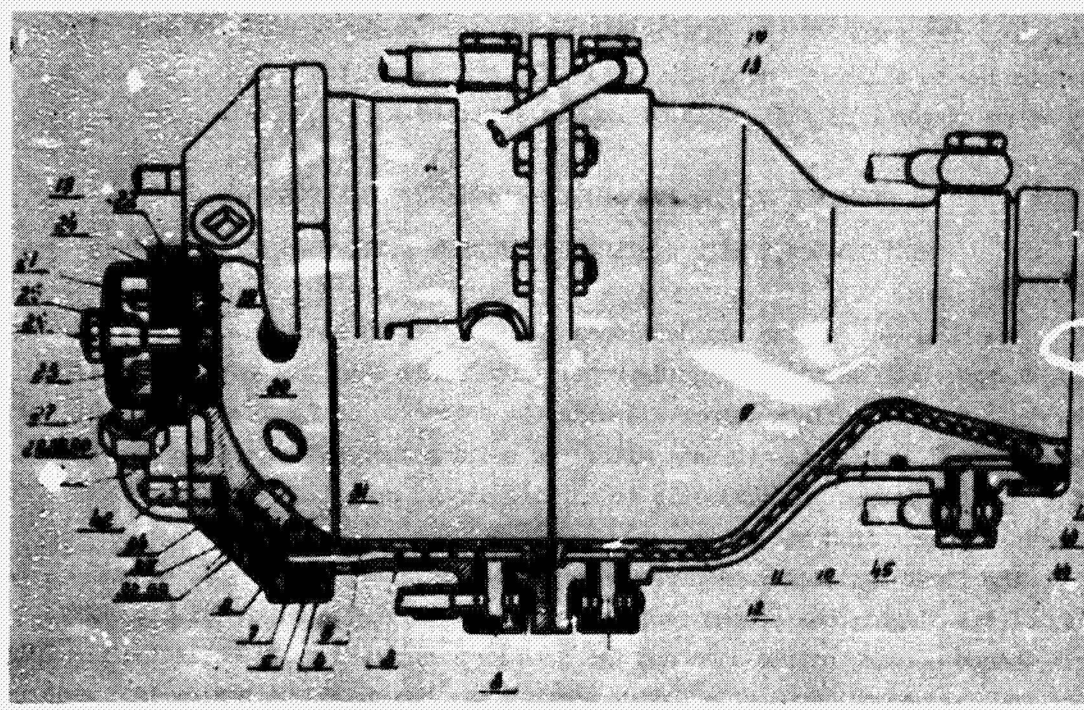


Fig. 5
Schematic of the Alcohol-Kerosene, Multiple-Firing RDK-150 LPRE

This engine featured the same design decisions successfully realized in the "RDA-1-150" nitric acid engine, VIZ., an injection, cylindrical combustion chamber, dual-propellant external cooling--the nozzle with alcohol, the cylindrical combustion chamber with liquid oxygen--and a staged ignition system with electrical spark and modular construction. The following technical data characterized the performance of the "RDK-1-150" engine:[11]

1.	Thrust	70/160 kg.
2.	Pressure in the chamber	5/11 atms.
3.	Specific impulse	150/210 sec..
4.	Pressure of fuel feed	8/20 atms.
5.	Diameter of sections of the nozzle	37.5/64mm.
6.	Volume of the combustion chamber	1.8 L.
7.	Overall dimensions	340 x 220 mm.
8.	Weight	8.5 kg.
9.	Duration of an uninterrupted firing	180 sec.
10.	Operating lifetime	20 min.

Test stand firings produced data close to the pre-test calculations. Gro[illegible] tests of the "RDK-1-150" engine in a model of the glider "G-14," staged to te red ..gned as a rocket glider, were conducted in 1940. Flight tests of the engine proved unsuccessful. The value of the "RDK-1-150" engine development resided in utilizing designs similar to those of the nitric acid LPRE, and showed the possibility and advisability of an oxygen LPRE that could be ignited repeatedly.

A COMBINED SOLID- AND LIQUID-PROPELLANT ROCKET ENGINE, THE "KRD-604," WITH A STEP-UP THRUST OF 1,100-TO-5,000 kg

The "KRD-640" engine was developed in 1939-1940 on the basis of combining in a single design, both solid and liquid-propellants. This combination of two types of engines was accomplished in a manner allowing the engine to be fired at first as a solid propellant engine with a high thrust; after the solid propellant supply in the chamber had burned away, it switched automatically to burning liquid propellants with a lesser thrust, but with an increase in duration.

The first ignition guaranteed a high starting acceleration and, naturally, the accuracy of the flight; the second ignition ensured the length of the flight. Nitroglycerine-based powder, nitric acid and kerosene were employed as propellants, the latter fed into the chamber by means of a solid-reactant gas generator. A device that switched the engine automatically from solid- to liquid-propellants and triggered the gas generator, was the chief design feature. The peculiarity of this design involved unifying within the body of the rocket propellant tanks and a propellant feed system without piping and intermediate compartments.

The schematic of this "KRD-604" engine, and that of the "RDD-203" rocket in which it was utilized, are shown in Figure 6.[13] The "KRD-604" engine produced the following data:[12]

1.	Thrust	4,500/1,030 kg.
2.	Pressure in the chamber	220/48 atms.
3.	Specific impulse	200/220 sec.
4.	Pressure of liquid fuel feed	75 atms.
5.	Diameter of sections of the nozzle	39/132 mm.
6.	Duration of firing	0.7/9 sec.
7.	Total impulse of thrust	12,300 kg./sec.
8.	Volume of combustion chamber	18 L.
9.	Overall dimensions of the chamber	950 x 203 mm.
10.	Weight of the assembly	46 kg.

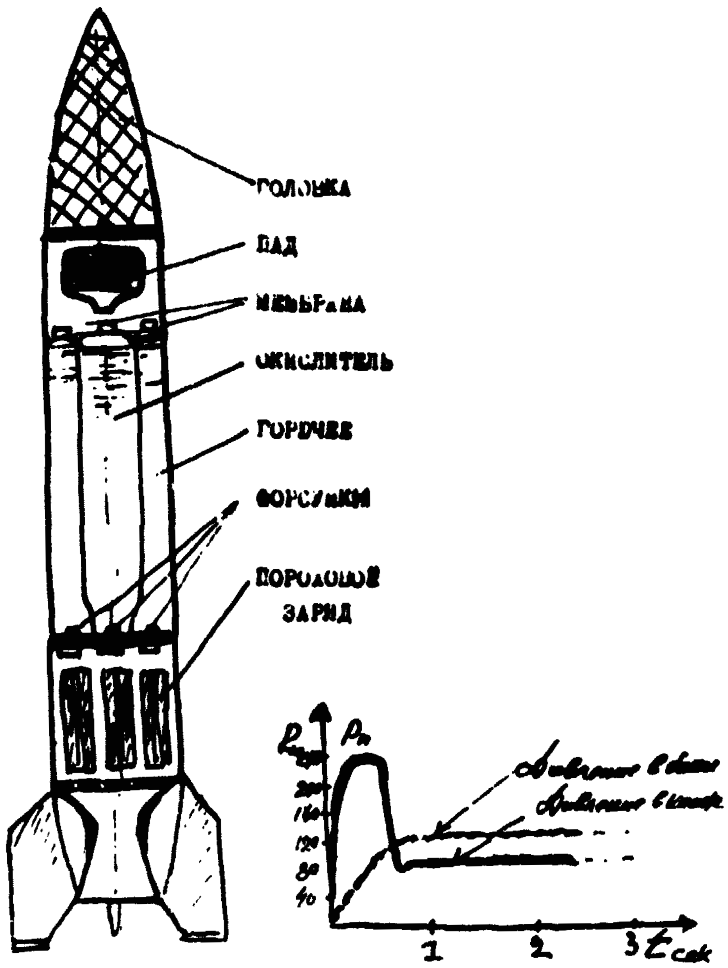


Fig. 6
Schematic of the Installation and Components in the Rocket with the Combined Solid- and Liquid-Propellant KPD-604 Engine

In 1940-1941, test launches of the combined "KRD-694" engine in the "RDD-203" rocket—which had an initial weight on the order of 180 kg—achieved distances of about 20 km (against a calculated distance of 22.5 km).[14] A view of the "RDD-203" rocket on the launch stand for single and group launches is shown in Figure 7.

THE NITRIC ACID LPRE "D-1-A-1100" WITH A CONTROLLABLE THRUST OF 350-1, 400 kg, FOR ROCKET AIRCRAFT

The "D-1-A-1100" engine was designed in 1941 and assigned as a basic engine for application in rocket aircraft interceptor. Nitric acid and kerosene, fed into the

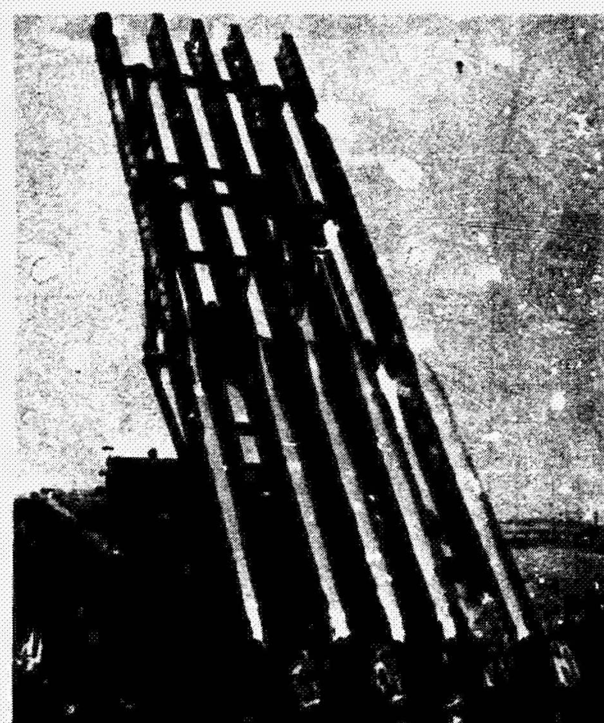


Fig. 7
View of the Mobile Launcher for Multiple Firing of RDD-203 Rockets With Combined Rocket Engines in Firing Position, September 1940.

chamber by a pressure-fed system, served as propellants. The design schematic of this engine is shown in Figure 8. The engine design basically corresponds to the 150 kg-thrust "RDA-1-150" engine described earlier.

The "D-1-A-1100" engine possessed the following basic technical data:[5]

1. Thrust . . . . 1,400/350 kg.
2. Pressure in the chamber . . . . 19/5.8 atms.
3. Specific impulse . . . . 203/150 sec.
4. Pressure of fuel feed . . . . 48/17 atms.
5. Diameter of sections of the nozzle . . . . 39/132 mm.
6. Volume of the combustion chamber . . . . 19 L.
7. Overall dimensions . . . . 730x310 mm.
8. Weight of the chamber with valves . . . . 48 kg.
9. Duration of an uninterrupted firing . . . . 180 sec.
10. Operating lifetime . . . . 20 min.

During the creation of the "D-1-A-1100", great effort was expended in solving technical and production problems (primarily in connection with the nozzle and its

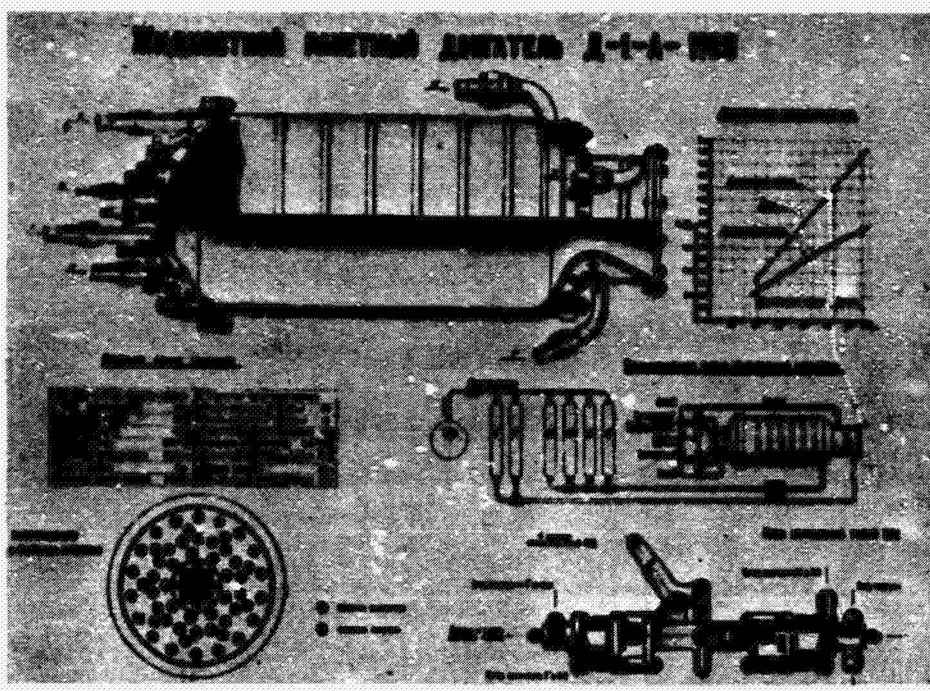


Fig. 8
Schematic of a DI-A-1100 Nitric Acid and
Kerosene LPRE for the Rocket Plane "BI."

cooling) of this "scaled-up" engine that produced ten times more thrust (in a single chamber design) than had its prototype. In the course of the work, research was conducted to establish the true quantities of heat flow and its distribution along the length of the chamber and nozzle. Special metallographic studies based on the evaluation of the critical points during phase transformation of the metals were made of the nozzle after firing the engine.

Testing of this engine was successfully completed in April 1942, and it was ready for installation in the "BI" aircraft, designed under the direction of V. F. Bolkhovitinov. The first test flight took place on May 15, 1942, with G. Ya. Bakhchivandzhi as the pilot, and was recorded as the first Soviet manned flight of a rocket interceptor aircraft. A picture of the "BI" plane before takeoff appears in Figure 9.

Fig. 9
A View of the Rocket Plane "BI-1" and of the D-I-A-1100
Engine Before its First Flight, May 15, 1942.

SELF-CONTAINED AIRCRAFT LPRES OPERATING ON NITRIC ACID AND KEROSENE WITH A PUMP-FED PROPELLANT SYSTEM: THE SINGLE-CHAMBER "RD-2M" AND DUEL-CHAMBER "RD-2M3V"

We began work on the creation of self-contained LPREs with a pump-fed propellant system in 1940, and it became the subject of intensive work after 1942, when the limitation in the "BI" aircraft of a pressure-fed propellant system became apparent. As a result of the extensive design study carried out in 1942-1943 and experimental work performed in 1944, two models of automatic LPREs burning nitric acid and kerosene with a pump-fed propellant system were developed, built, and stand-tested under laboratory conditions: the single-chamber "RD-2M" with a variable thrust in the range of 350-1,400 kg, and the dual-chamber "RD-2M3V" with a thrust of 100-1,500 kg, each identical in construction and design of the basic models, but distinguished from each other by the range of the variable thrust. Both worked according to the same principle. The design of the d[illegible]l-chamber "RD-2M3V" engine is shown in Figure 10.

Four basic subsystems characterized these engines: the combustion chamber, steam-gas generator, turbine pump unit, and the ignition-regulating subsystem, mutually interconnected by a single pneumatic-hydraulic system which guaranteed their automatic functioning and control of ignition, engine operation, and the cessation of burning by means of controls located in the cabin of the aircraft. The combustion chambers were

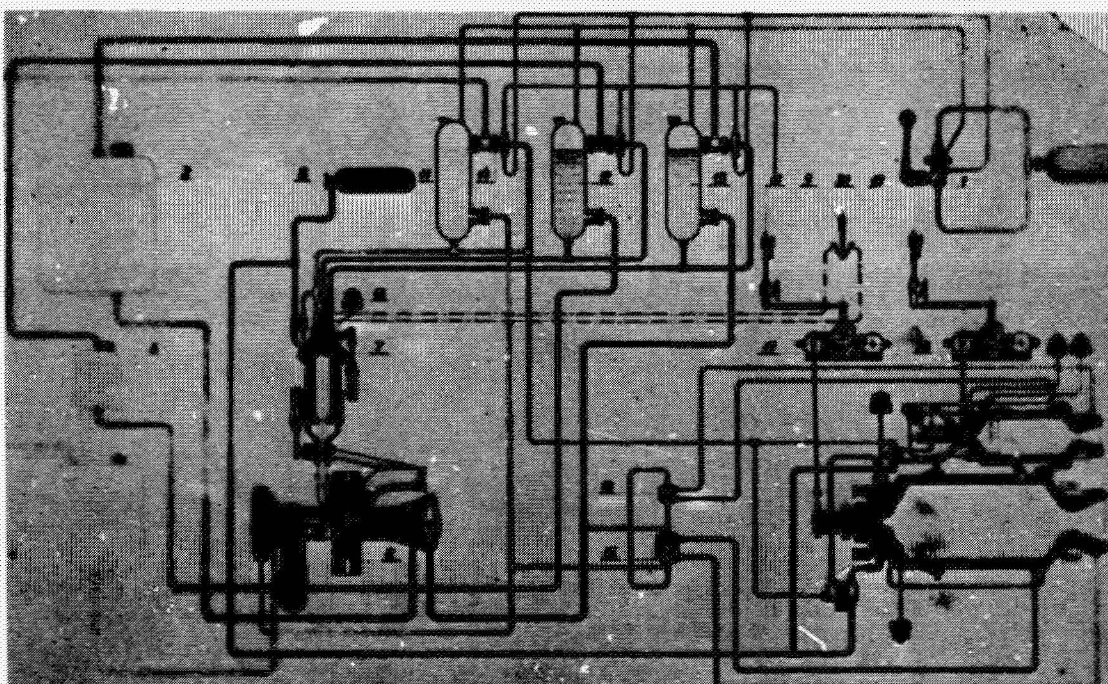


Fig. 10
Schematic of a Double-Chamber Flight Engine AD-2M3B, Using
Nitric Acid and Kerosene With a Pump-Fed Propellant System

similar in design to the "D-1-A-1100" engine, but were different in the design of the start-stop propellant control valves for multiple firing in flight.

The vaporizing generator (PGG) worked on the basic propellant components, with water or an alcohol solution injected in the burner for cooling purposes which automatically regulated the temperature of the vapor. The PGG was developed taking into account previous design experience at RNII.

The turbine-pump unit (TNA), developed with the participation of the National Institute of Hydromechanical Construction, consisted of two single-stage centrifugal pumps for feeding fuel and oxidizer into the chamber, and a separate pump for feeding the alcohol solution into the PGG. The supply to the pumps used a two step turbine fed directly from the PGG.

The start-regulating system (PRB) for these engines fulfilled a dual role. First, it served as a device for ensuring multiple firing of the engine, and possessed a microsystem of the pressure-fed system used for starting the PGG. Second, it served as a regulating device in the engine to control the thrust, and also supported the stability of a given pattern and flow return of the propellants into the tanks during periodic shutdowns.

The basic subassemblies of the engines just enumerated and other related components were combined into two modules: the chamber and the pumps, thus permitting their distribution together or separately in different compartments of the aircraft. A photograph of the chamber system of the "RD-2M3V" is shown in Figure 11 and the pumping module in Figure 12.

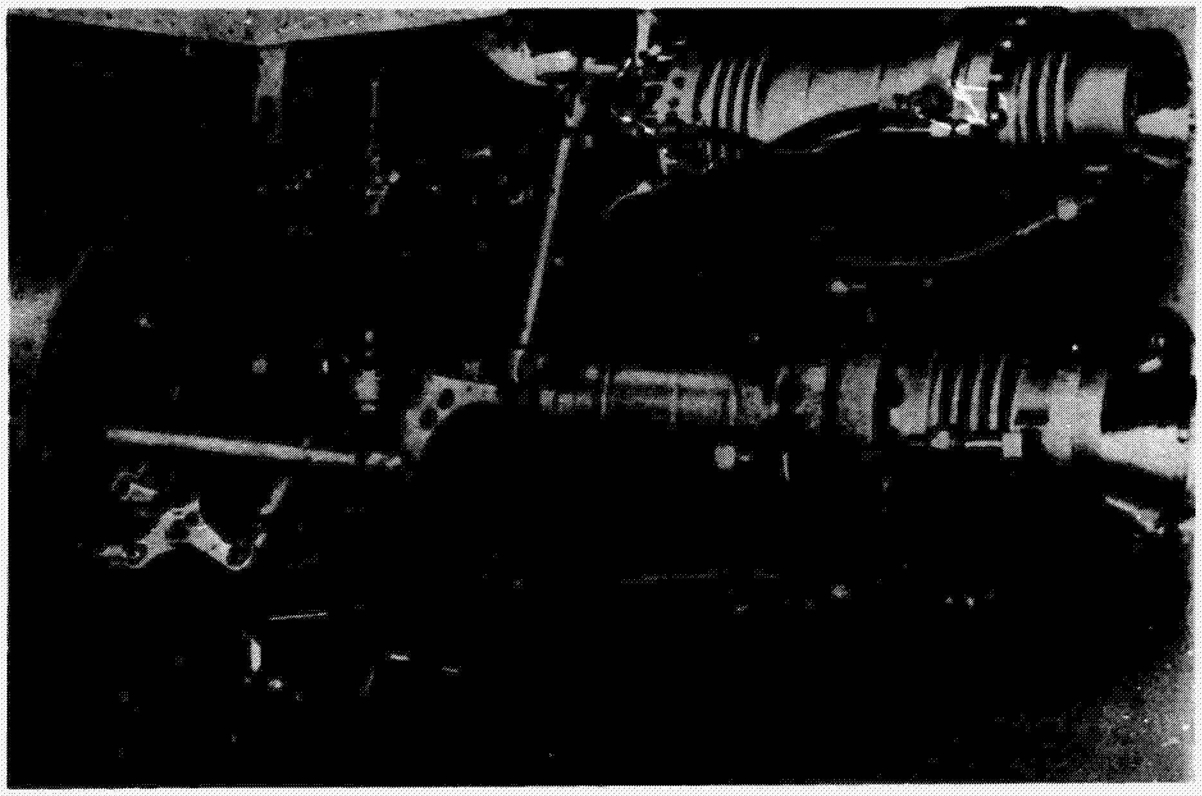


Fig. 11
View of the Chamber Module of the Pump-Fed RD-2M3V Engine

The basic performance data for these engines appears below:

		"RD-2M"	"RD-2M3V"
1.	Thrust	1,450/400 kg.	1,500/100kg.
2.	Pressure in the chamber	20.5/6.7 atms.	20/6 atms.
3.	Specific impulse	200/142 sec.	200/145 sec.
4.	Pressure of feed	44/10 atms.	35/10 atms.

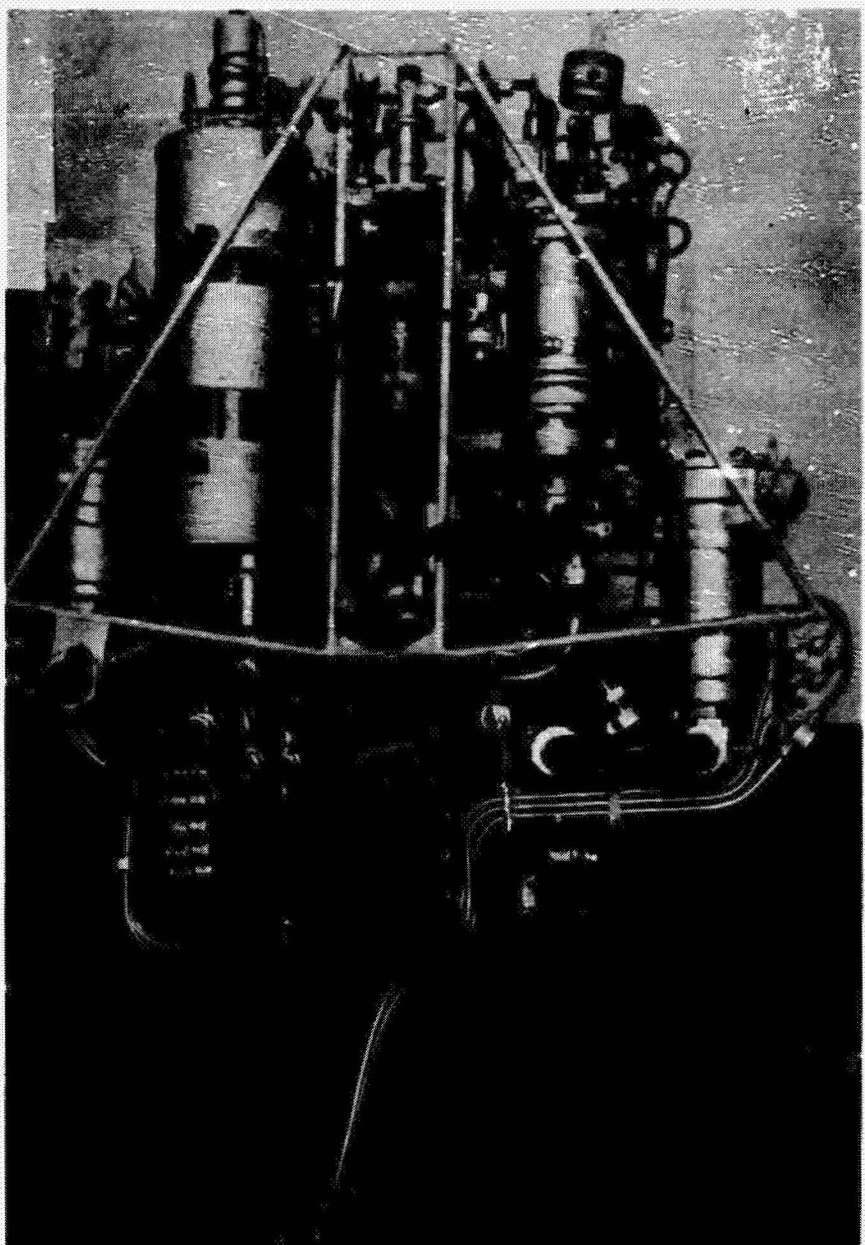


Fig. 12.
View of the Pumping Module of the Pump-Fed RD-2M3V Engine

		"RD-2M"	"RD-2M3V"
5.	Diameter of sections of the nozzle	80/146 mm.	80/146; 35/90 mm.
6.	Volume of the chamber	18 L.	18/4.5 L.
7.	Overall dimensions of the chamber block	925x225 mm.	925x540x220 mm.
8.	Weight assembled	200 kg.	223 kg.
9.	Turbine power and RPM	75 HP/12,500rpm	80 HP./12,000rpm.
10.	Operating lifetime	40 min.	1 hr.

The "RD-2M" and the "RD-2M3V" engines were successfully tested from January through April 1945 in test-stand experiments under government control and provided revealing data; they became the first models of Soviet automatic aircraft LPREs that featured pump-fed propellant systems with multiple start. During tests in flight and when assembled in the experimental rocket aircraft "I-270", the engines proved reliable. A photograph of the "I-270" is shown in Figure 13.

Fig. 13
A View of the Rocket Plane With the RD-2M3V Engine
Before its First Flight in September 1947.

In concluding my paper I think it is necessary to stress that this survey of LPREs is only a small part of the scientific and technical work undertaken in this field in the USSR between 1934-1944. Moreover, these experiments demonstrated the independent and self-reliant paths adopted in the Soviet Union for mastering the LPRE and for introducing new technology, as well as the originality in solving the major scientific and technical problems connected with LPRE designs of different types and requirements.

We recognize the importance of F. A. Tsander's role in this work, but it is impossible not to mention the exceptionally fruitful, collective work of many engineers, designers, and experimenters, a large amount of whom were followers of his school. Their energy, persistence, and capacity were shown at different times in achieving positive results during the testing and design development in the field of LPRE.

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