

The First Russian LOX-LH₂ Expander Cycle LRE: RD0146

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I. Introduction

In the USSR, three LOX-LH₂ liquid-propellant rocket engines (LRE) engines of particular interest were developed. The RD-56 engine of 7.5 tf thrust level was developed by Konstruktorskoe Buro Khimicheskoe Mashinostroenie (KBKhM, Korolev) in early 60-s. The RD-57 engine of 40 tf thrust level was developed in the "Saturn" Design Bureau («Saturn» DB, Moscow), at the same time. Both engines were developed for the USSR Moon program. The RD0120 engine with 200 tf thrust level was developed in Konstruktorskoe Buro Khimavtomatiki (KBKhA, Voronezh) in 70-s for «Energia-Buran» program. All three engines are staged combustion cycle engines. In the 90-s, the RD-56 engine was modified into the KVD1 engine for LV upper stages. The work on the RD-57 engine was stopped in 70-s and the work was stopped on the RD0120 – in early 90-s due to the «Energia-Buran» project stoppage.

The first USSR rocket-building company that used LOX-LH₂ LRE for boosters using the expander cycle to drive the TPA turbines was «Energia» («Energia» RSC, Korolev). In 1988, «Energia» RSC awarded KBKhA to produce the RO-95 LOX-LH₂ engine without gas generator for «Buran-T» and «Vulcan» LV boosters. At that time, the P&W RL10 engine was the only upper stage expander cycle LOX-LH₂ engine. The RL10 had been in flight operation 30 years. In 1958, P&W started developing the LR-115 engine version, the prototype of RL-10 engine.

The RO-95 LOX-LH₂ engine produced 10 tf thrust with a specific impulse of 475 s. Ground fire testing was planned to start in 1991-1992. The groundwork for such engine development was based on KBKhA's experience in development of the RD0120 LOX-LH₂ engine for the «Energia» LV, based on thorough experimental production and an active test facility. Comprehensive analysis performed by «Energia» RSC and KBKhA confirmed the obvious design advantages and high reliability of the expander cycle. Selection of the RO-95 engine was influenced by a rare occurrence in the development of USSR space technology. Before that time, closed expander cycle engines were not used in the USSR and its studies were not financed. However, the flight operation of the RL-10 engine (Pratt & Whitney) provided the designers in the USSR experimental confirmation of the high reliability of the expander cycle engine. While work on the RO-95 engine was stopped after preliminary design, this engine might be considered as a predecessor to the first modern Russian expander cycle LOX-LH₂ RD0146 engine.

After 10 years, the Russian rocket companies returned to the expander cycle of LOX-LH₂ engine. In 1999, M. Khrunichev Center awarded a technical specification to KBKhA for the RD0146Y expander cycle LOX-LH₂ engine of 10 tf thrust level for «Proton» and «Angara» LV upper stages, and in 2002 «Energia» RSC awarded to KBKhA for the RD0146Э engine of 10 tf thrust for «Omega» LV. Russian development of a new generation expander cycle engine attracted Pratt & Whitney's interest that later resulted in a contract award for the RD0146 engine development.

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II. RD0146 Engine Specifications



RD0146 engine
 $I_{sp} = 451 \text{ kgf}\cdot\text{s}/\text{kg}$

Thrust in vacuum, tf:	
at thrust main stage mode	10
at thrust final stage mode	5
Specific impulse in vacuum, kgf·s/kg	451-463
mixture ratio	5.9
Pressure in chamber, kgf/cm ²	81
Propellant parameters at engine inlet:	
oxidizer:	
temperature, K	81-91
pressure absolute static, kgf/cm ²	-2.6
fuel:	
temperature	
pressure absolute static, kgf/cm ²	1.3-2.1

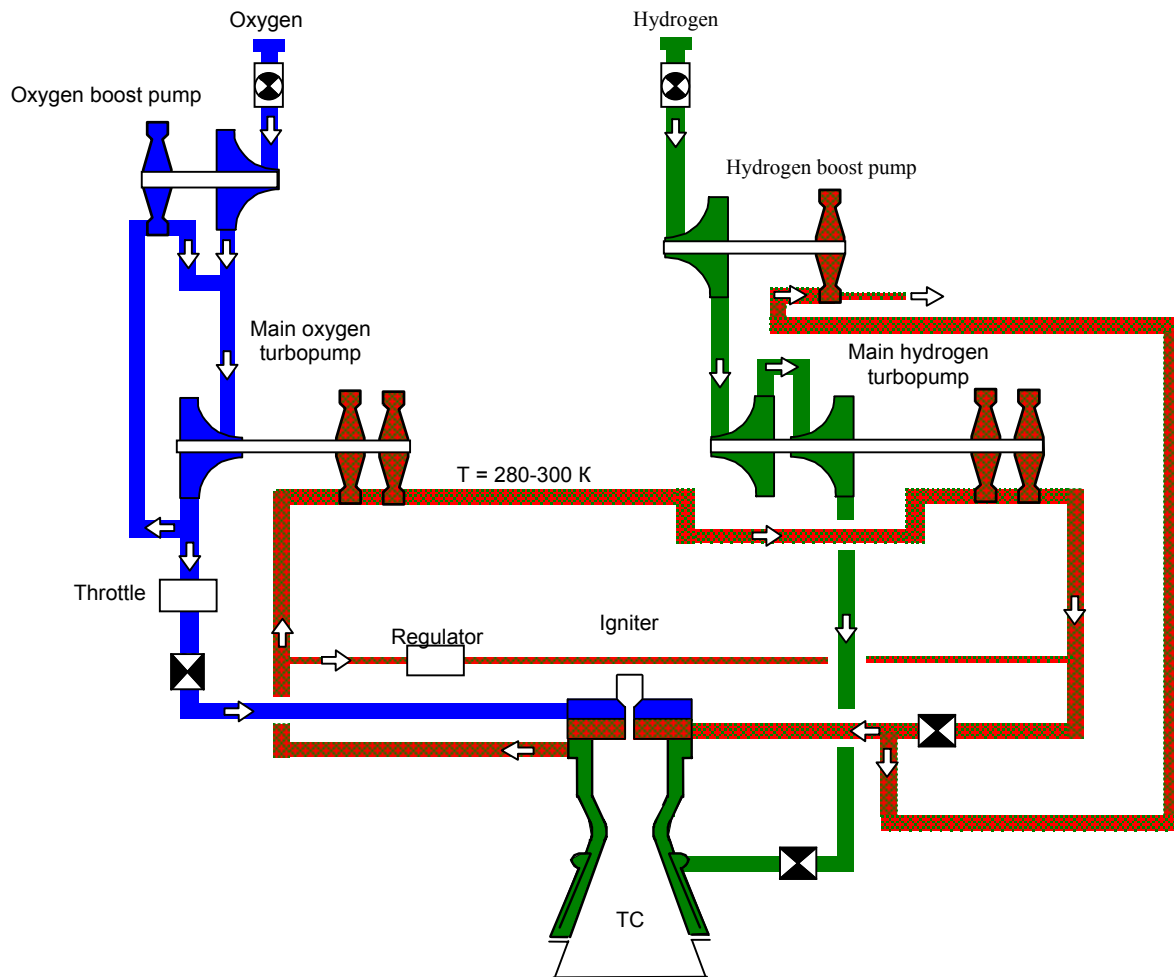
Number of starts within a flight,	1-5
Application factor,	1
Duration, s,	
not more	400-1100
Dimensions, mm, no more than	
length	1880-2440
nozzle exit diameter	960-1250
Engine "dry" weight, kg, no more than	196-261



RD0146 engine
 $I_{sp.} = 463 \text{ kgf}\cdot\text{s}/\text{kg}$

III. RD0146 Engine Flow Schematics

The engine flow schematic includes LOX and LH₂ supply ball-valves and boost pumps to use low inlet pressure propellants and to enable high rotation speeds of both of the main pumps. The hydrogen boost pump is driven by a small flow of gaseous hydrogen. The hydrogen is provided by a two-staged hydrogen pump that increases pressure to over 260 atm. The hydrogen pump is driven by a two-staged turbine. The entire hydrogen flow is supplied to a regeneratively cooled thrust chamber (TC) to cool the chamber hot wall and to heat the hydrogen. To achieve the required hydrogen heating in the chamber cooling duct the cylindrical part of combustion chamber is longer than it is in gas generator engines and its hot wall has over 200 longitudinal fins. Maximum temperature at the fin top is not more than 900 K. Hydrogen flows out of the chamber cooling duct at 280-300 K and then goes to the LOX and LH₂ TPA turbines. After providing the required power to both turbopumps, the hydrogen gas is supplied through about 200 coaxial injectors into the combustion chamber. Combustion efficiency for these injectors is approximately 99.5%.



Liquid oxygen is supplied to the LOX boost pump and then to the main LOX turbopump inlet. The LOX boost pump is driven by a hydraulic turbine, where LOX is supplied from the main LOX pump outlet. The single-staged main LOX turbopump increases oxygen pressure up to 130 atm and supplies it to the combustion chamber. A Hydrogen-rich mixture is provided to the chamber and ignited by an electric-plasma igniter that operates under low pressure with excess oxygen. Engine ignition occurs in a preliminary stage which is stabilized for a short period of time prior to throttling up to the 100 % thrust level. Engine shut-down is hydrogen-rich in order to maintain chamber integrity. Before each start, the engine is thermally conditioned to prevent cavitation. Propellant mixture ratio is set by a regulator; thrust level is supported by a throttle valve. Engine valves are driven by pneumatic and electromechanical actuators.

IV. Design Features of the RD0146 Engine

During the design, manufacturing and final development of the RD0146 we've used design solutions developed for LOX-LH₂ engine RD0120 as well as a number of new innovations, i.e.:

- use of hydrogen and oxygen ball valves at engine inlet because the hydraulic resistance of such valves is practically the same as the hydraulic resistance of a straight section of cylindrical pipeline;
- the main hydrogen and oxygen turbopumps are made separately;
- the main hydrogen turbopump rotor speed is 123,000 rpm – this corresponds to the spec characteristic of its bearings 3.08×10^6 mm×rpm; this allows max efficiency of pumps and turbine and to reduce the turbopump weight;
- high speed rotor supports/bearing providing elastic damping while high speed rotor balancing ensures minimum vibrations.
- non-cooled nozzle section made of carbon composite material to provide required thrust specific impulse;
- ignition with the help of electric ignition device that allows for multiple restarts and re-use; laser ignition device for this engine is under development;
- mathematical model of expander-cycle engine to reduce experimental study and verification costs;
- mathematical model of engine start in vacuum to define conditions for engine ground test without imitation of vacuum conditions;
- cooling fin design of the combustion chamber hot wall to provide additional hydrogen heating in the chamber cooling path and to reduce CC overall dimensions and weight;
- Capability to shut down safely upon depletion of any propellant;
- new high-strength nickel-based alloys and heat-resistant steels that allow to reduce the CC mass by ~ 30 % in comparison with conventional materials applied in the LOX-LH₂ engine RD0120;
- modern titanium and aluminum alloys for housing parts and internal parts of units;
- powder technologies for titanium and steel components;
- provision of “artificial” roughness of hydraulic channels; electric discharge method for blade manufacturing and electrochemical blade processing in the monolithic turbine wheel;
- separate experimental testing of engine systems at test stand in order to provide preliminary check-out of autonomous engine systems without their mutual influence upon each other;
- use of engine CC igniter device to address in-tank propellant phase separation before the engine start-up;
- performance of hot-fire tests with the use of the engine control and safety system based on the “floating” commands – programmed control, i.e. the initiation of subsequent commands only when the engine achieves the required state. This allows to avoid many irreversible states and hazardous situations that may lead to failure of hot-test or to damage of tested hardware;
- engine safety system with 0.995 coverage coefficient and 100 % reliability of the software.





Oxygen boost pump



Hydrogen boost pump



Main oxygen pump parts



Main oxygen pump parts, manufactured by powder technology (HIP) method



V. Agreement with Pratt & Whitney

In March 2000 by Pratt & Whitney initiative "The Engine RD0146 Selling Agreement" was signed by KBKhA and Pratt & Whitney. The first phase of the Agreement included manufacturing and delivery of an RD0146 engine mock-up by KBKhA to Pratt & Whitney, and later manufacturing and delivery of a test engine to Pratt & Whitney for demonstration firing. The engine delivery date was scheduled as December 2000 for the engine mock-up, and May 2001 for the test-bed engine. In March 2000 when the Agreement was signed, the RD0146

engine a component manufacturing was already started and the test-beds for engine and component testing were reconditioned. KBKhA had to produce an engine using new and untested approaches. All the works were at the initial phase, and there were no more than 14 month available to achieve the complete results - the delivery of an operable test engine. Because of KBKhA's prior uncompleted work in this area this expedited schedule was not unreasonable. By its nature LRE development activities often encounter unexpected delays. The RD0146 development activities were no exception. The delays were caused by production delays at KBKhA's subcontractors. Nevertheless, the live fire test of the first RD0146 Russian LOX-LH₂ expander cycle engine was successfully conducted on October 9, 2001, 18 months after signing the Agreement. This test confirmed the system development performed by KBKhA in 1999.

The delivery of the test engine to Pratt & Whitney was postponed by agreement between both sides while additional technical tasks to prove the engine performance were accomplished. The certification firing test of RD0146 № 2, intended for the delivery to Pratt & Whitney, was successfully conducted in December 2002. All the Pratt & Whitney technical requirements proving the operability of the delivered RD0146 № 2 were fulfilled. In March 2003 the engine was sent to Pratt & Whitney.

The RD0146 Amendment with Pratt & Whitney was the second foreign contract of such technical complexity in KBKhA's history. Time and the results of team-work proved the importance of the Agreement for KBKhA's and its development lines:

- KBKhA confirmed its technical authority and contract reputation in Russia as well as abroad. The high technical quality of LRE development in Russia was demonstrated;
- A world class company, Pratt & Whitney became KBKhA's stable foreign customer and team mate, KBKhA and Pratt & Whitney cooperative abilities grew to include export on KBKhA license agreements;
- the team work between specialists in both countries were developed and improved, their communication expanded. An atmosphere of mutual confidence was created which is the key to success for future joint product;
- Additional systems in the area of hydrogen LREs were supported and further matured;
- Additional funds were received;
- the necessity of continuation and expansion of mutually beneficial international cooperation was demonstrated.



RD0146 engine mock-up
for Pratt & Whitney



Operable RD0146 engine №2
for Pratt & Whitney

VI. Distinctive Features of RD0146 Engine Development

It should be noted that the sufficiency of funding has a significant impact on engine development. It is clear that the era of unlimited financing of LRE developments in the space industry by the leading countries is over. This makes engine developers look for ways to reduce LRE development costs. Commercial customers are reluctant to finance projects unless the propulsion provider has provided a valid demonstrator, either full-scale or sub-scale. This requires engine companies to finance their own advanced LRE development. The RD0146 engine development used a combination of state, customer, and developer financing; moreover, these finances were in series rather than in parallel and unstable in respect to the scope and timeliness. It is natural that all these factors increase the risk of engine development program.

Several oxygen-hydrogen LRE development schemes existed prior to the RD0146 such as the J-2, SSME engines in USA, and the KVD1 and RD0120 in the USSR. These engines provided background data such as the number of development engines and total cost and time of the development program.

By increasing the number of restarts and the mean LRE test time the number of test engines can be decreased. The number of repetitive tests of Russian developmental LREs is characteristically in the range from 1.3 to 3.2, while the same parameter for American LREs is over 10 times higher – from 16.2 to 41. The comparative analysis of Russian LREs development parameters shows that development in the USA is performed with fewer developmental engines. Moreover, the mean testing time and mean number of repetitive tests for an American developmental LREs is considerably higher than the same parameters for Russian LREs.

Analysis of different types of oxygen-hydrogen LRE development, both Russian and foreign, established the basic recommendation for the RD0146 engine development approach, taking into account its thrust level (10 tf), pneumatic and hydraulic systems, design, low cost manufacturing, testing and maintenance during development:

- the scope of individual component testing should not be reduced;
- system level component development should be carried out before engine tests;
- operating environment simulation should be as realistic as possible;
- the development must be focused on one development engine. Tests of this engine must include:

Development tests for initial study of the engine characteristics, including operability at 100 % thrust mode; development tests to ensure all technical requirements are met – startup & shut down transients, control system, multiple starts. Also, it is necessary to obtain the information necessary to optimize the final engine design.

Engine qualification tests to define parameter ranges in which the engine is operable and to specify final engine design.

- one test engine must ensure the maximum number of tests with to increase the test time;
- to maximize the time on one test engine the engine may be inspected and maintained between tests. The engine reparability and maintainability parameters should be developed early in the development process;
- during engine development, components and subassemblies repair sets should be available for use on the development engines;
- the scope of technical diagnostics, both post-test and during testing, must be fully developed, as well as the health monitoring system to prevent test engine distress should emergency situation occur;
- manufacture a limited number of development engines to the final engine design and test in identical conditions to compare their characteristics and confirm the engine technical specifications;
- manufacture the engine(s) for final development tests, perform tests, and confirm producibility through LRE acceptance tests.

The engine development run programs and results are included in the pages that follow.

Test № 1 – engine RD0146 # 1 test, October 9, 2001 – initial test of new cycle engine.

Test № 2 – control-technology test for test engine RD0146 # 3, start of research tests, engine quality confirmation prior to delivery to Pratt & Whitney.

Tests № 3-7 – continuation and completion of research and confirmation tests of RD0146 # 3. In Test № 4 RD0146 # 3 reached 100 % thrust.

Test № 8 - control-technology test of RD0146 # 2, planned for delivery to Pratt & Whitney. Duration – 65 s.

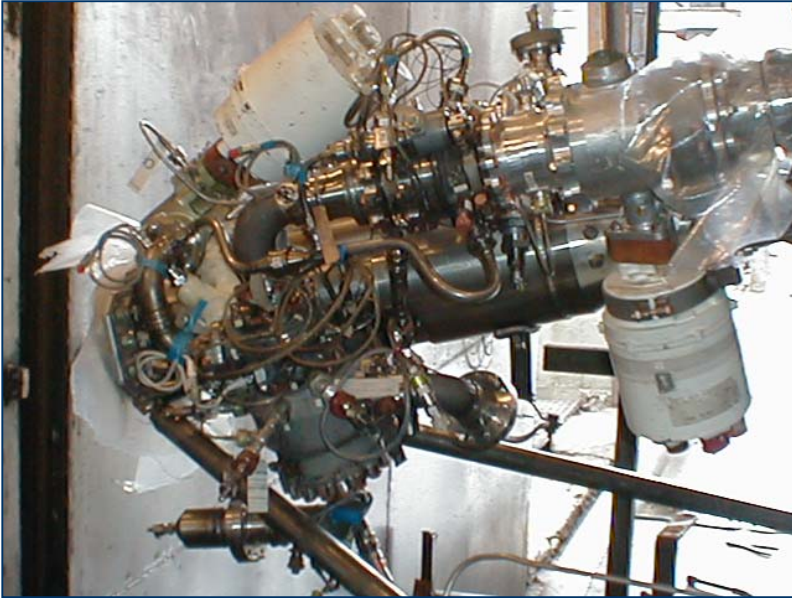
Tests № 9-25 – development tests of RD0146 # 3. 17 short tests with initial, steady state, and final thrust in each run. The following accomplishments were made: start up problems under different conditions, shut down problems, multiple engine start up with minimal time between tests, etc.

Tests № 26-29 – continuation of development tests of test engine RD0146 # 3, engine life tests and development tests for flaw detection. The following issues were solved: mixture ratio regulation, augmentation and throttling according to chamber pressure, engine design chill down, etc. engine test at 100 % thrust was increased to 200 s.

27 tests of energy units RD0146 UE1, UE2, UE3 and 29 fire tests of engines RD0146 # 1, 2, 3 have been carried out without emergencies hardware loss.

EXPERIMENTAL UNITS

Three Independent segments of a Full-Scale Engine
Standard Component Mounting and Standard Components Operation



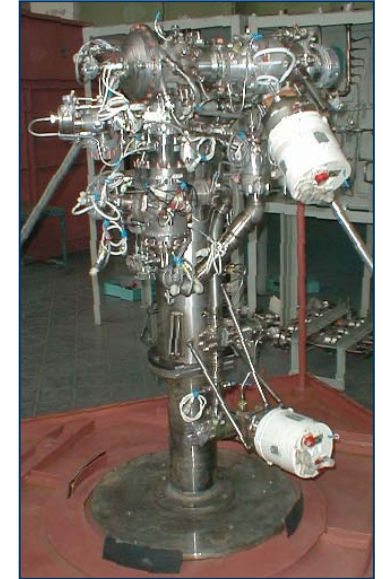
I. Experimental Unit RD0146.UE1

All oxygen system components.
5 LOX tests, up to 108 % of nominal mode



I. Experimental Unit RD0146.UE2

Chamber with igniter and controls
components.
15 fire tests were carried out, up to
52 % of nominal mode.



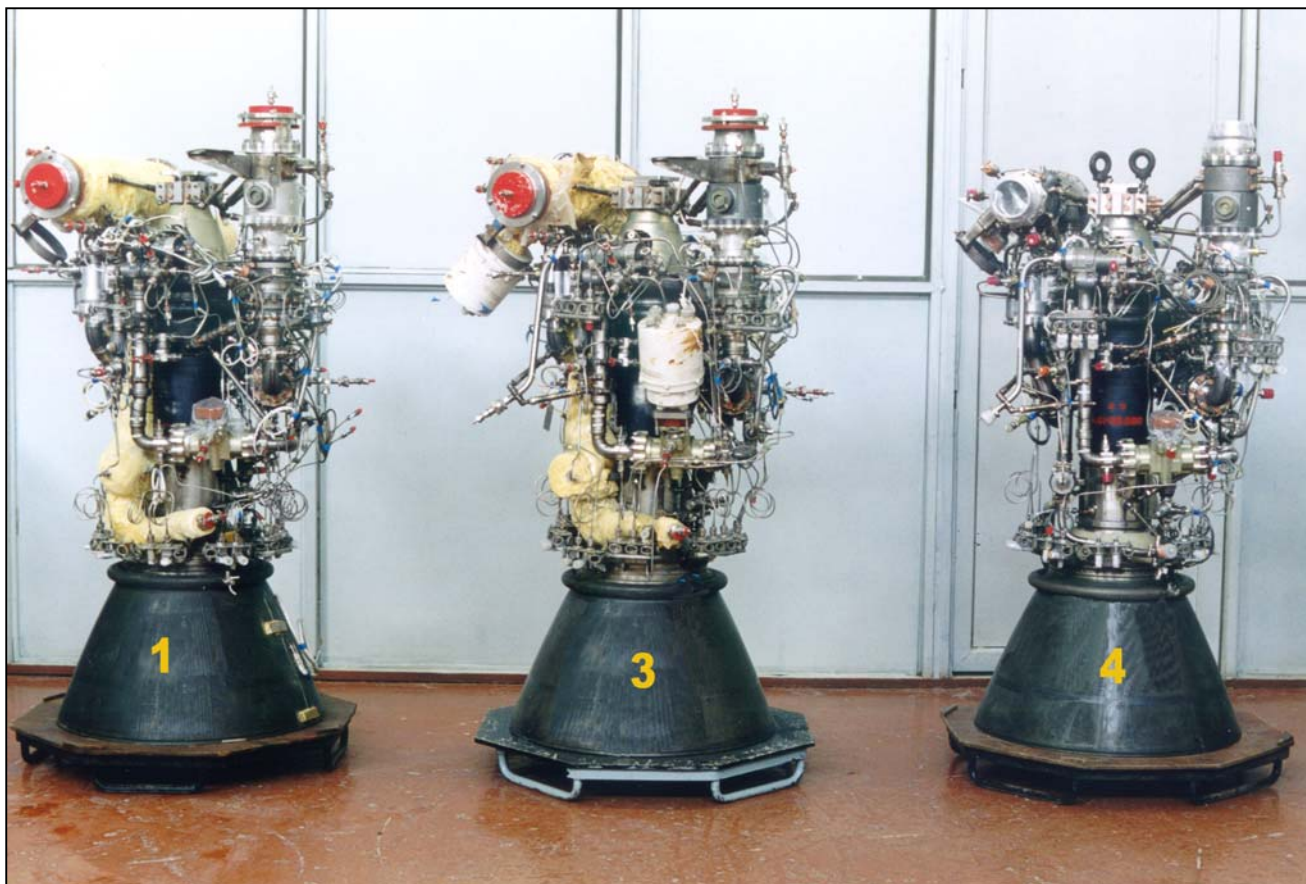
III. Experimental Unit RD0146.UE3

All hydrogen system components.
7 LH₂ tests, up to 118 % of nominal mode



RD0146.UE2 test

Test Bed Engines RD0146 № 1, 3, 4 Produced by KBKHA



RD0146 Engine № 1– One short-term firing test was conducted October, 9 2001.

RD0146 Engine № 3 – 27 research and development firing tests were conducted. Engine is ready for additional firing tests.

RD0146 Engine № 4 – New engine.

KBKhA Hydrogen Test Facilities

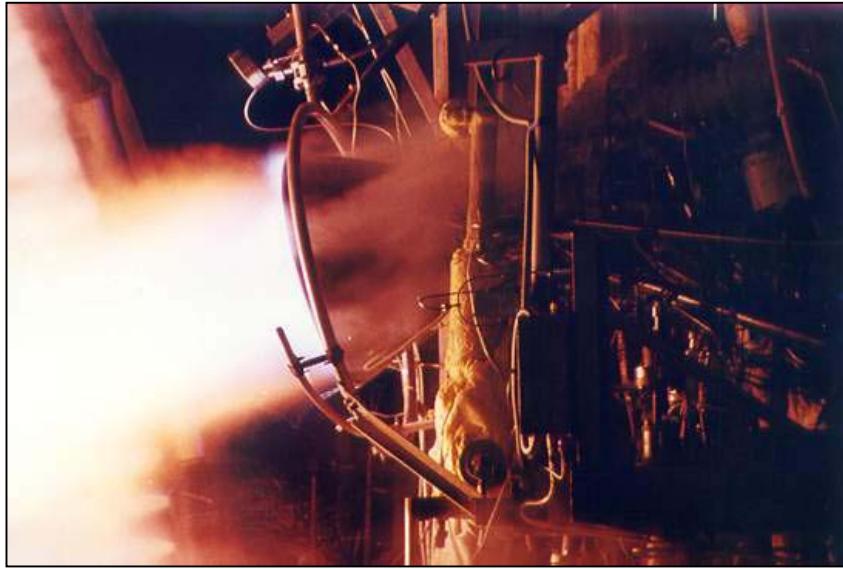


Inclined LOX-LH₂ (kerosene) test for 100 tf thrust engines.

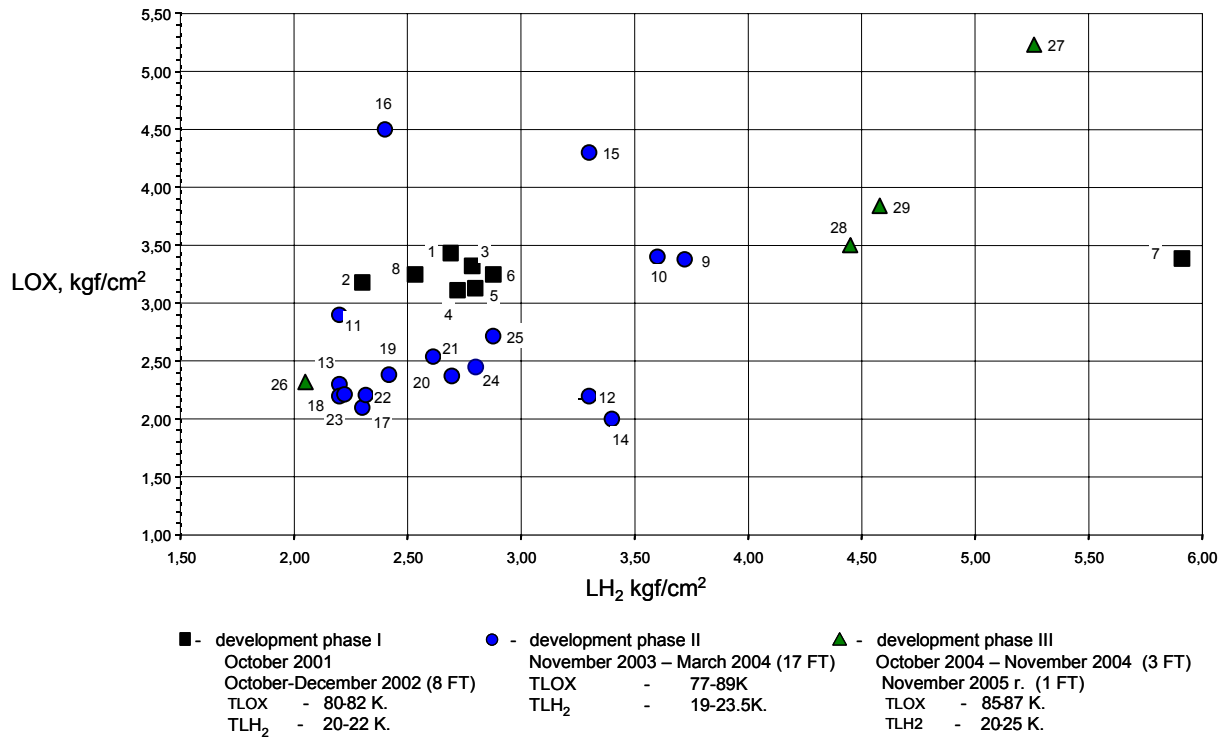
LH₂ production and storage plant – gaseous hydrogen output – up to 120 m³ per hour, LH₂ – up to 5 kg per hour. Firing test rate – one test every 10 days. Maximum test duration – 230 sec.

VII. RD0146 Engine Firing Test Execution 1st Phase Main Results

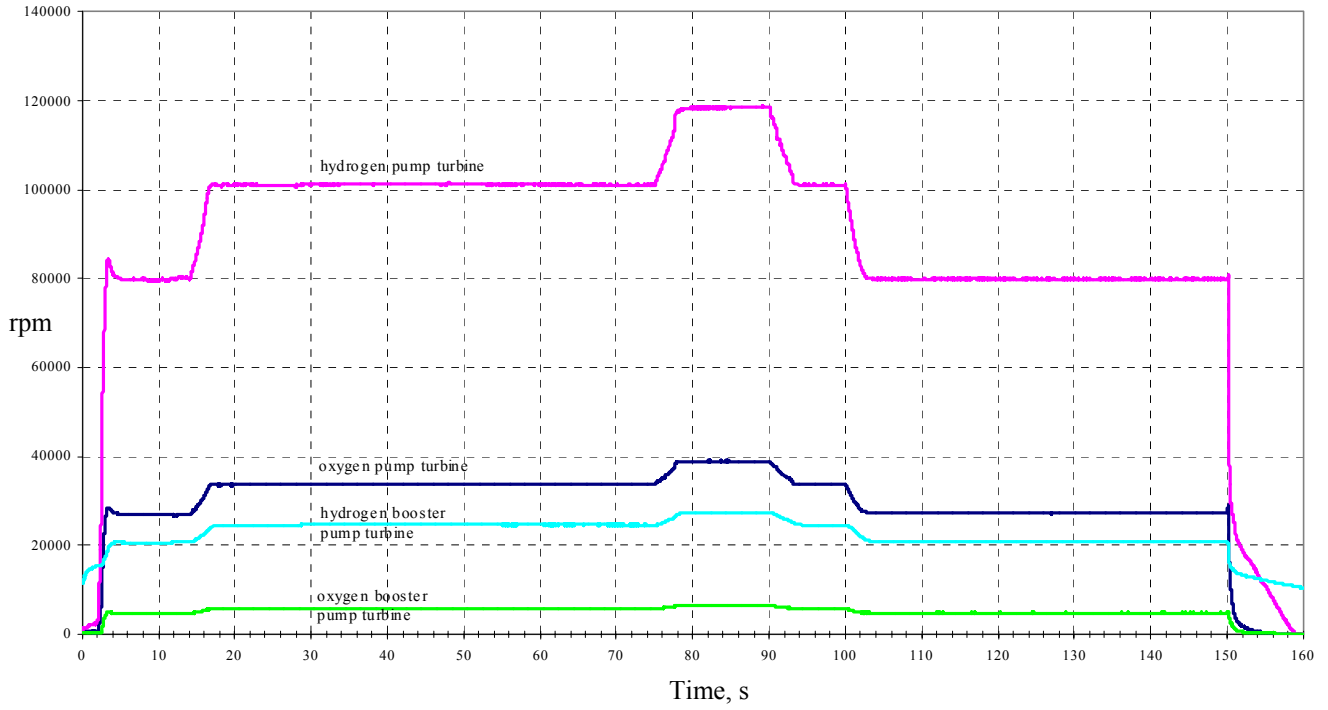
1. Number of engines tested	3
2. Number of engine firings, on one engine	29 27
3. Total operating time for three engines, sec, including on one engine	1582 1507
4. Maximum operating time for single engine, sec:	
100 % and more	705
80-100 %	437
less than 80 %	365
5. Single engine starts in one day, minimum time between the starts - 6 minutes.	8
6. Engine structure temperature before the start, °C	-50 - (+55)
7. Engine chamber pressure before starting, kgf/cm ²	0.07
8. Components temperature at the engine inlet, K:	
Oxygen	77-89
hydrogen	19-25
9. Components pressure at the engine inlet, kgf/cm ² :	
Oxygen	до 5.2
hydrogen	до 5.8
10. Mixture ratio range, %	±11
11. Chamber pressure range, %	40-112.5
12. Hydrogen temperature at the chamber head inlet, °C	+40 - (-10)
13. Engine operating point recovery after throttle transition	stable
14. Engine start uncontrolled time duration, sec	0.42-0.73
15. Engine start uncontrolled time dependence on structure and components temperature	minimal
16. LH ₂ quantity used during engine and engine systems development testing, ton	19.5



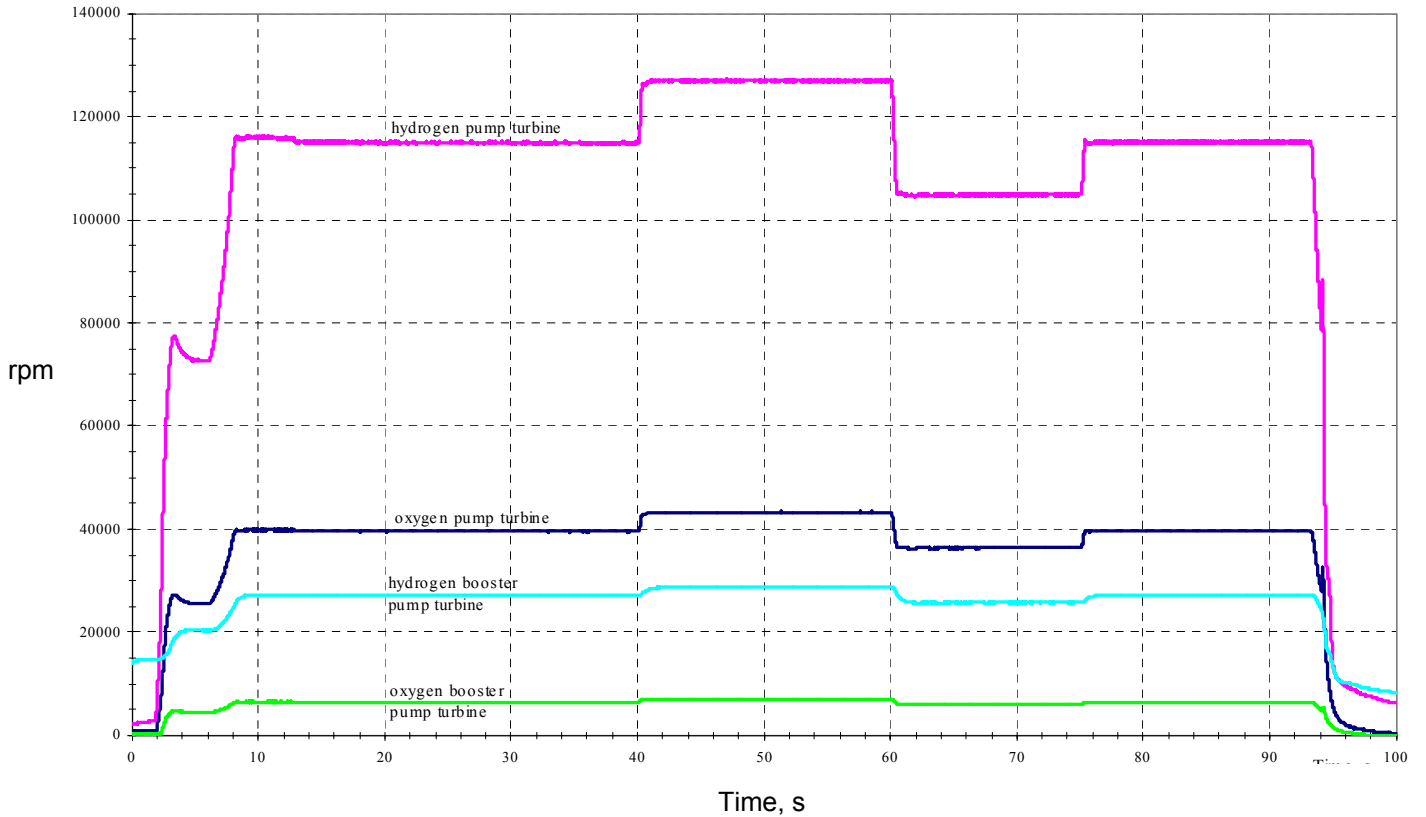
RD0146 Firing test

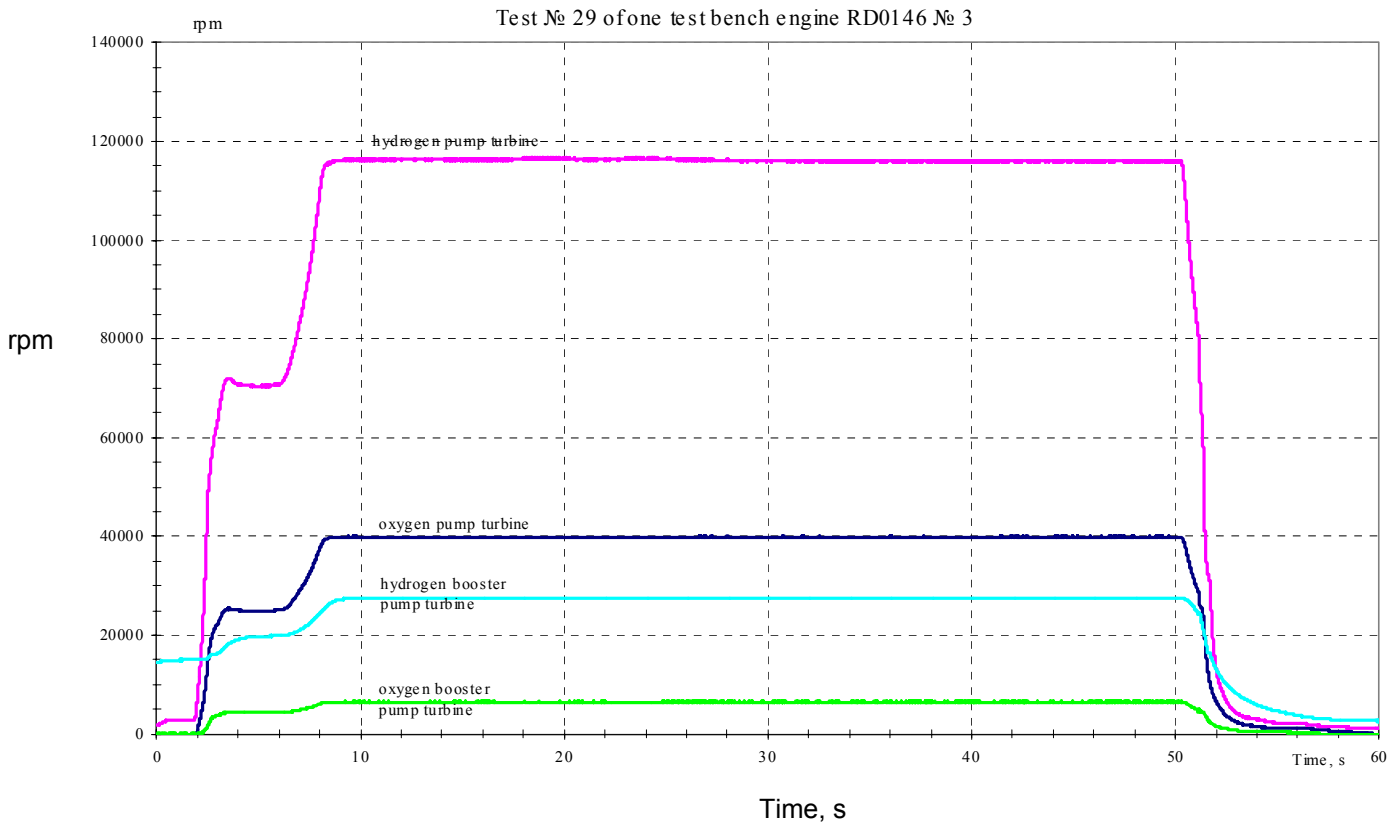


Test № 4 of one test bench engine RD0146 № 3,
on which this engine reached 100 % thrust mode for the first time



Test № 27 of one test bench engine RD0146 № 3





VIII. Conclusion

KBKhA will proceed with RD0146 LOX-LH2 expander cycle engine development. This engine clearly demonstrated the significant advantage of expander cycle compared to gas generator for the engines of this thrust level.

According to some classifications of LOX-LH2 LRE, some are classified as "Super-cryogenic" because both propellants are cryogenic. "Super-cryogenic" development and R&D work on the actual LOX-LH2 engines the cryogenic components and engine firing tests not only demonstrate high scientific and designer qualification, but also is the most reliable way to maintain and develop such capability.

RD0146 engine development and its results prove that the first Russian RD0146 LOX-LH2 expander cycle engine exists as a real operable engine.