

# Development of LM10-MIRA LOX – LNG expander cycle Demonstrator engine

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## Abstract

This article contains results of joint works by Konstruktorskoe Buro Khimavtomatiki (KBKhA, Russia) and AVIO Company (Italy) on creation of the LM10-MIRA liquid-propellant rocket demonstrator engine for the third stage of the upgraded “Vega” launcher.

Scientific and research activities conducted by KBKhA and AVIO in 2007 – 2014 in the frame of the LYRA Program, funded by the Italian Space Agency, with ELV as Prime contractor, and under dedicated ASI-Roscosmos inter-agencies agreement, were aimed at development and testing of a 7.5 tons thrust expander cycle demonstrator engine propelled by oxygen and liquid natural gas (further referred to as LNG).

## 1. Introduction

In 2004, when the development of the Vega launcher was still ongoing, ASI started the investigation of those potential areas where evolution of the launcher could be envisaged, with the aim to reach improvement of performance, reduction of costs, use of a liquid ‘green’ engine.

The feasibility study selected the ‘three stages’ configuration of the new launcher, named Lyra, and defined the main architecture of the propulsion system using liquid oxygen and methane.

Under the frame contract for ‘Lyra phase B’ committed by ASI to the Vega system architect ELV, the contractual collaboration on propulsion activities between KBKhA and AVIO started in 2007, under the umbrella of a dedicated inter-agencies agreement between ASI and Roscosmos, following the inter-government “*Agreement between the Government of the Italian Republic and the Government of the Russian Federation on Cooperation in the Exploration and Use of Outer Space for Peaceful Purposes*”, signed in Moscow on 28th November 2000.

The first phase of joint works on the LM10-MIRA engine was aimed for the concept design of the 10 tons-class thrust LM10-MIRA flight engine propelled by liquid oxygen and LNG. Successful completion of this phase of activities in 2008 allowed to start the next phase of works that involved design, manufacture and testing of the 7.5 tons thrust LM10-MIRA demonstrator engine (further referred to as the demonstrator). In June, 2014, LM10-MIRA Demonstrator engine firing test campaign has been successfully accomplished at Voronezh (Russia) premises.

In order to conduct the contractual activities, a joint team of AVIO and KBKhA leading specialists was formed. The team successfully completed the scope of design, manufacturing and testing works in full compliance with both European and Russian standards.

## 2. Design and manufacture of the demonstrator engine

The demonstrator was designed and manufactured on the basis of jointly developed and mutually approved technical specifications that reflected requirements to the components design and characteristics.

In process of the demonstrator’s development, designers took into account the scientific and technical base on the oxygen-hydrogen RD0146Y expander cycle engine created by KBKhA by request of Roskosmos. By now, the RD0146Y engine has been tested for 77 times and its total operation is over 4000 c. The use of expander cycle has confirmed high reliability, simplicity of design, low development cost and good performance of the engine.

It is necessary to mention that LM10-MIRA contractual activities involved usage of a background unique bases created independently by KBKhA's and Avio in the field of liquid propellant engines, within the frame of the Russian Space Program and of the Italian national research program.

*Development of the RD0110M open cycle generator engine*

In order to demonstrate the possibility of transferring the RD0110 oxygen-kerosene four-chamber liquid-propellant rocket engine to the oxygen-methane version, KBKhA conducted design, experimental and technological activities. As a result, in 1998, an engine fuelled by LNG was fire tested. The engine was named RD0110M. In the course of testing, a scope of assigned tasks was successfully solved and the possibility of the engine's transfer to LNG with minimal design changes was confirmed.

The RD0110M engine and the picture of its fire test at KBKhA's test facility is given in Figure 1.



Figure 1. RD0110M engine and its fire test at KBKhA's test facility

To be noticed that up to now the original oxygen-kerosene RD0110 engine has been successfully used in the "Soyuz" carrier rocket.

*Development of the RD0146M expander cycle engine*

The RD0146M engine created by KBKhA on the basis of the oxygen-hydrogen engine components is fully founded on design and technological solutions for the RD0146 engine. In 2007, at KBKhA test facility, a cycle of the RD0146M fire tests was successfully conducted with 6 ignitions and total operation time of 200 s.

In process of the RD0146M engine test preparation and testing, KBKhA gained unique experience of work with LNG, successfully solved a set of tasks on implementation of stand technologies for working with LNG as well as the tasks on experimental development of multiple engine start-ups during one startup day.

The RD0146M engine and engine fire testing is shown in Figure 2.

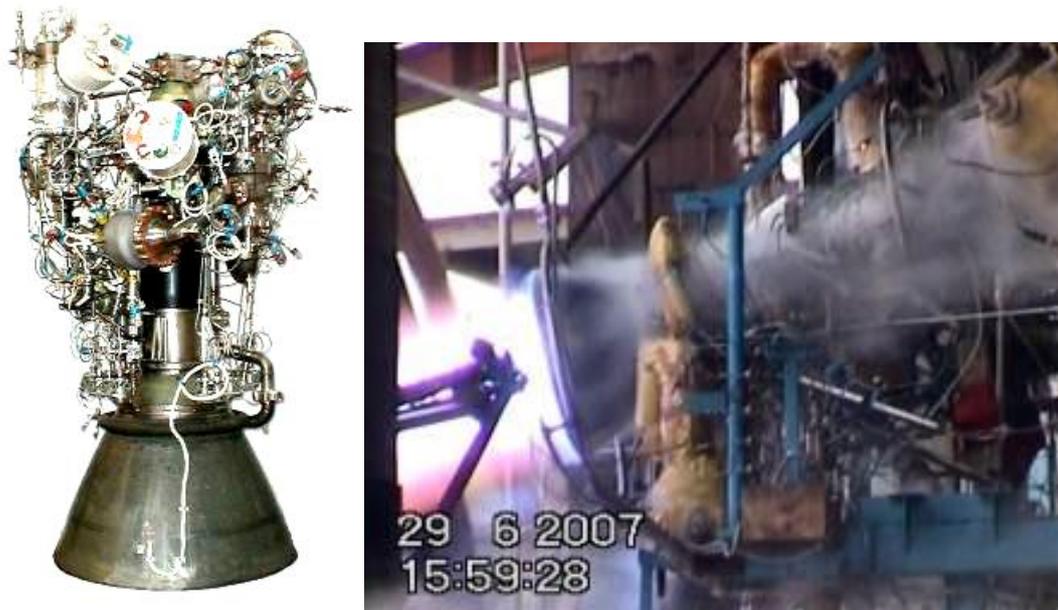


Figure 2. RD0146M oxygen-methane engine and its fire test at KBKhA's test facility

*Scientific and technical works on creation of oxygen-methane engines for prospective carrier rockets within the frame of the Russian Space Program*

Since 1998, KBKhA conducts scientific, research, experimental and design activities aimed at creation of the LOX – LNG liquid-propellant rocket engines with a wide range of thrusts to be used in prospective carriers.

Thus, by the beginning of 2007, KBKhA had a significant scientific and technical base in development of LNG fuelled liquid-propellant rocket engines, and this fact significantly influenced the positive decision to sign the contract between KBKhA and AVIO.

Also AVIO side background obtained in the frame of Italian national under ASI patronage and international under ESA contracts activities has been profited for LYRA program.

*LOX/GCH4 Combustor Heritage*

At beginning of 2000, AVIO have completed realization of the firing test facility, so-called FAST2 facility and starts an experimental activities on LOX/GCH4 combustion testing. The Sub Scale Thrust Chamber Assy (constituted by chamber, injector head and ignition elements) designed and manufactured by external supply has been used for FAST2 facility commissioning (see Figure 3). This step was the preliminary one to achieve “know how” in test stand tuning and managing.

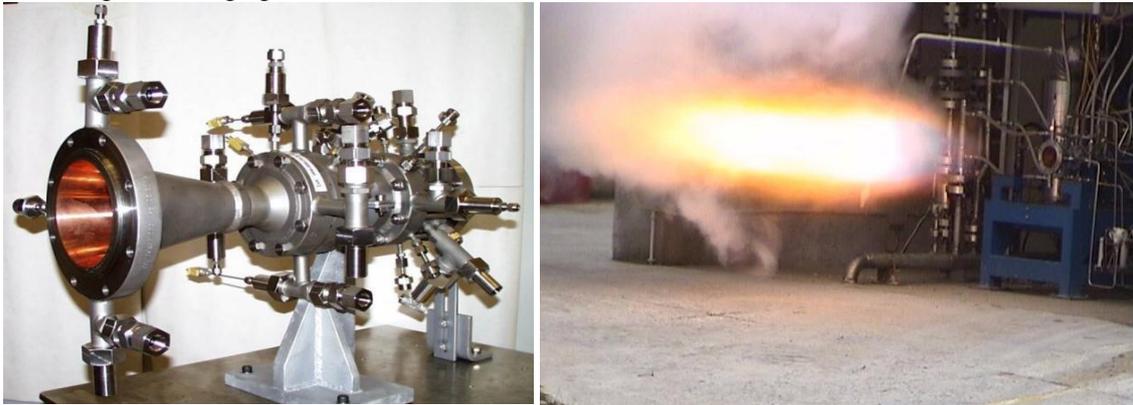


Figure 3 – LOX/GCH4 combustor and commissioning firing test at FAST2 facility

Following to first success, AVIO investigated the design and manufacturing of its Injector Head and Ignition System. In 2006-2007 the first Injector Head made by AVIO has been successfully tested with Igniter designed and manufacture by AVIO (see Figure 4). These activities were the base for the development of MIRA Sub-Scale Injector Head and for the MIRA Demonstrator Injector head design.

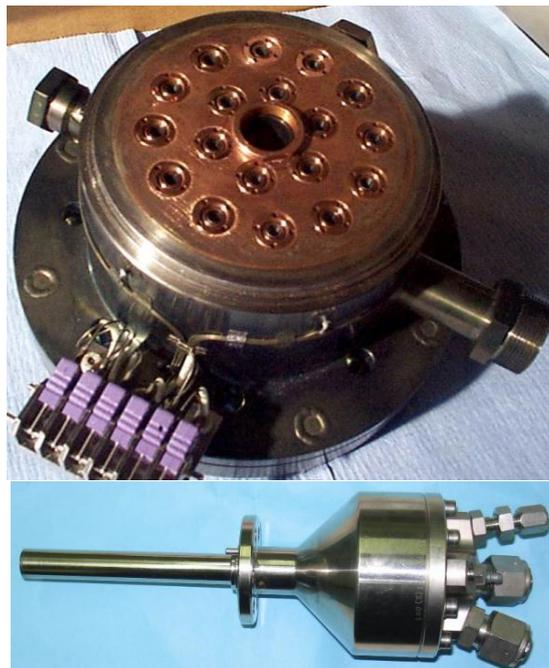


Figure 4 –AVIO First Injector Head and Igniter

*Turbopump Heritage for FTPA design*

AVIO since late 80's is designing and manufacturing Oxygen turbopump for the Ariane Oxygen/Hydrogen rocket engines. In particular Oxygen turbopump for Vulcain1 engine, Vulcain2 and Vinci were successfully designed, manufactured and tested (see figure 5). This is a results of years of research, tribological activity, technological programs, components testing and know-how. AVIO has also designed and manufactured rigs for subcomponents testing such as pump in water, bearing in LOx and seals in LOx/He/GN2. Such subcomponents activity was performed directly on AVIO bench premises in Colleferro (for pump-water testing) and Torino (for bearing/seals-Lox testing).

MIRA FTPA turbine design has been the results of turbine background in the aeronautic jet-engine.

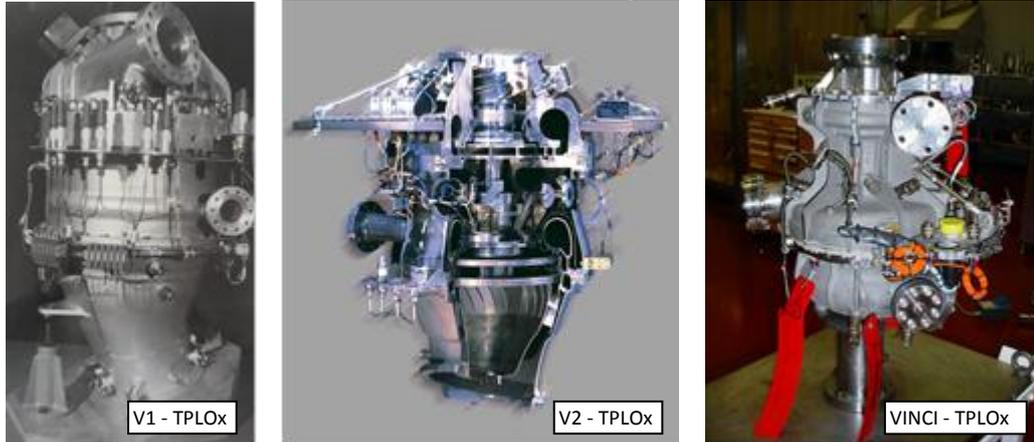


Figure 5. Vulcan 1/2 and VINCI oxygen turbopumps

Based on this owned experiences, KBKhA and Avio approached the design of the LM10-MIRA engine with a full share of the overall 'engine system' responsibility.

*LM10-MIRA Demonstrator engine*

A simplified scheme of the demonstrator engine is shown in Figure 6.

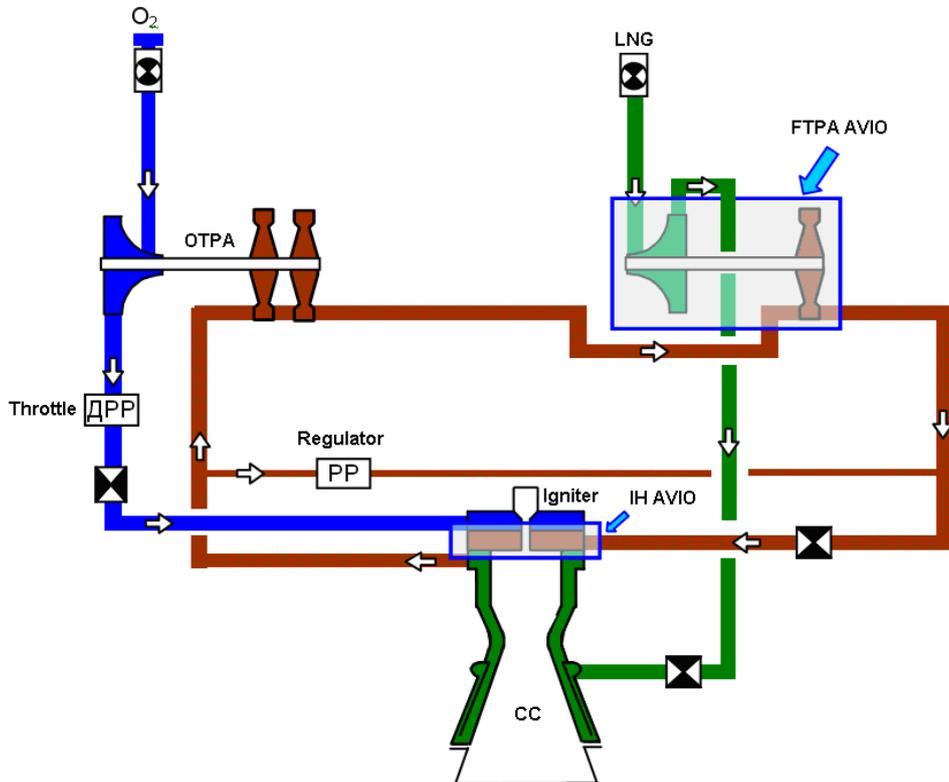


Figure 6. LM10-MIRA Demonstrator engine simplified scheme

Compared to the flight engine, the Demonstrator represents the identical thermodynamic cycle, architecture and thrust level, but it has been optimized with the final goal to minimize time and cost impact. Following to this objective the most part of prototype engine (RD-0146U KBKhA) has been used. At the same time, the critical components (Injector Head and Fuel Turbopump) needed for LNG application have been newly developed by AVIO.

#### *The chamber development*

In process of development, the chamber's thermodynamic, gas-dynamic and strength calculations were conducted. The demonstrator's chamber consists of the injector head created by AVIO and the chamber unit created by KBKhA. The design of Injector Head had involved several tasks that are schematically presented in Figure 7.

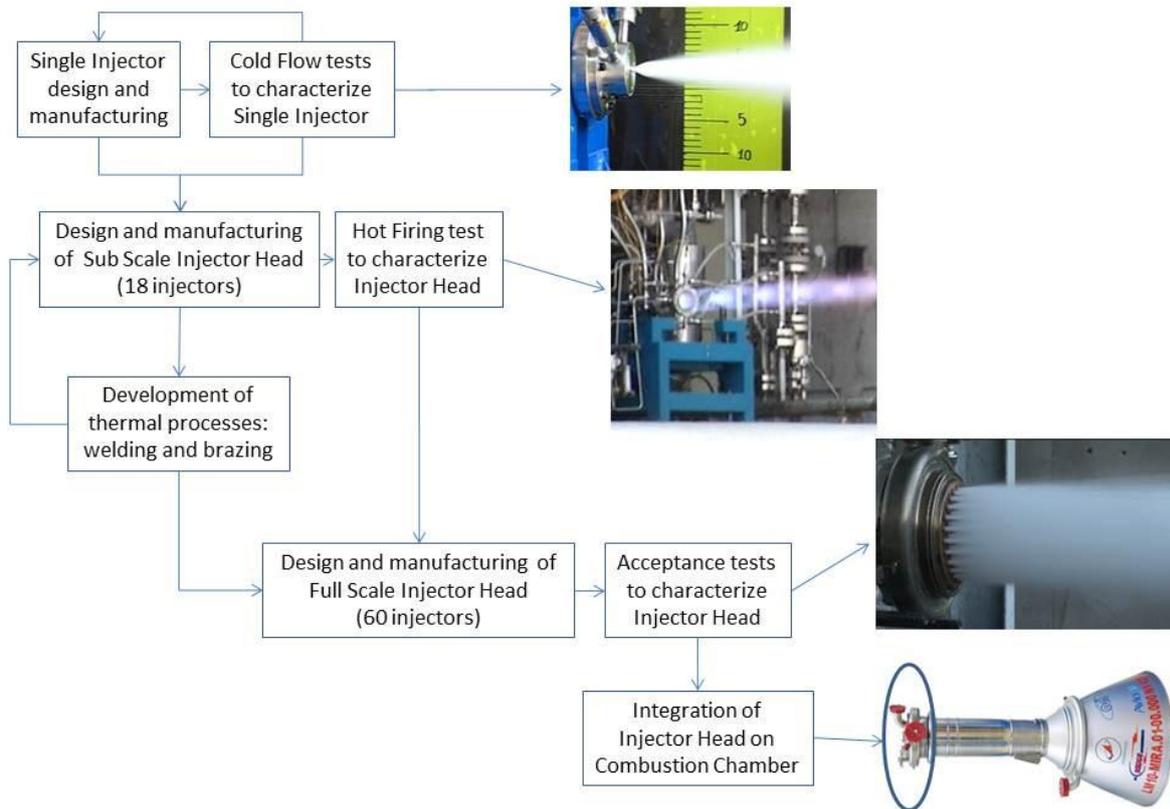


Figure 7. Development logic of Injector Head

The first step of Injector head design was the selecting of single injector element type. Many tests were performed on several types of injector: principally shear coaxial injectors and swirled one.

With testing activities performed on single elements, following skills have been learned:

- Link between injector performance and geometrical dimensions: injector recess, injector diameters at outlet section, injector length.
- Single injector layout with low deviation on performance: a single injector is generally made by at least two parts (posts + sleeves) and its mutual integration affects the overall performance of single injector.

In order to have a robust design, save cost and mitigate uncertainties on injector performance, the recessed shear coaxial element was selected.

Once selected the single injector element, the design of Sub Scale Injector Head (18 elements) was started and during this task technological issues were solved:

- dedicated thermal processes were developed in order to braze Inconel elements and to weld internal parts of Injector Head. Regarding the welding processes, traditional and laser welding processes were developed for Inconel elements.
- arrangement of internal parts of Injector head in order to minimize the time and cost to manufacture and integrate all parts and in order to maximize robustness and safety of Injector Head.

In order to confirm the performance of single injectors tasks, the Sub Scale Injector Head was tested in Colleferro in 2009-2010 with several hot firing tests. During these tests, the Injector Head performance measured were useful to check Single Injector performance in a wide range of mixture ratio and chamber pressure:

- the range of combustion chamber pressure achieved during test was 57-67 bar (the design value is 60 bar).
- the range of propellant mixture ratio achieved during test was 2.8 - 4.1 (the design value is 3.4).

After Sub Scale testing, the design of Full Scale Injector Head (60 injector elements) was started and skills (acquired during Sub Scale design) on internal Computational Fluid Dynamic analysis (reacting and frozen analyses) and Finite Element Model analysis was improved. The Injector Head resulting by the design tasks is presented in Figure 8.

In order to verify Injector Head behavior and characteristics, a dedicated tools and procedures were develop to perform cold test activity in Colferro (before integration of Injector to Combustion chamber).

Once verified the characteristic of Injector head, that completely fulfill the technical specification, the injector head and the chamber unit were welded together at the production plant of KBKhA. External view of the finalized and inspected thrust chamber assembly is given in Figure 9. The chamber nozzle outlet section diameter is 710 mm.



Figure 8. LM10-MIRA Injector Head



Figure 9. External view of the Thrust Chamber Assembly

In order to confirm the technical specification requirements, the chamber autonomous fire tests were conducted in the frame of the newly developed UE2 experimental unit. The scheme of the unit (see figure 10) and the fire tests program were developed by AVIO and KBKhA specialists. During the tests, the chamber was chilled by water.

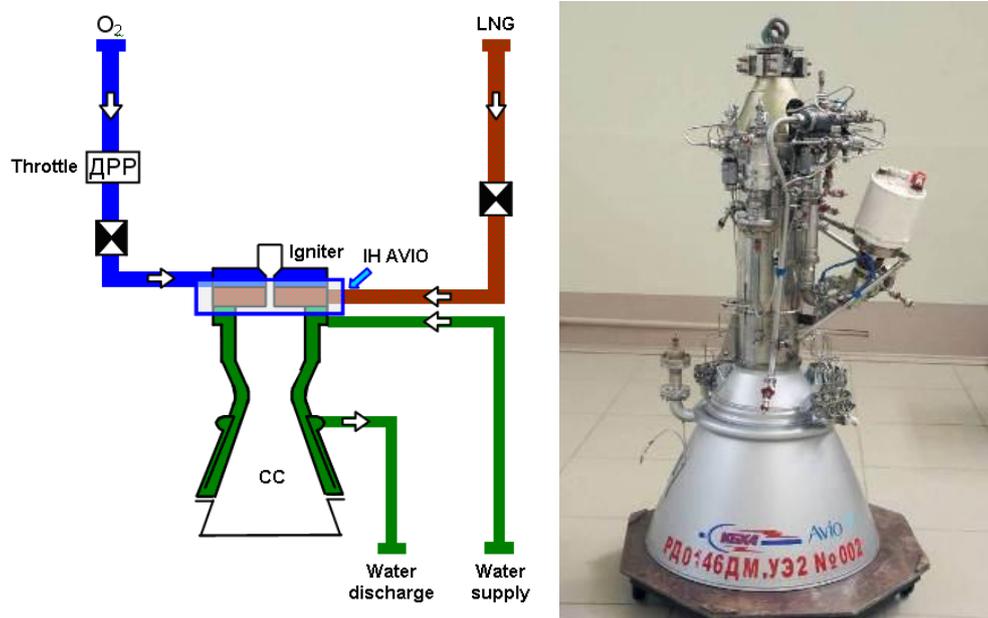


Figure 10. UE2 experimental unit

The program of UE2 tests conducted at KBKhA test facility included 7 firing tests with total duration of 118 s. In process of testing, parameters of the chamber reached the assigned values. The mixture ratio value 3.4 has been achieved. Full compliance with the test task requirements was achieved.

Figure 11 shows the UE2 unit during firing test.

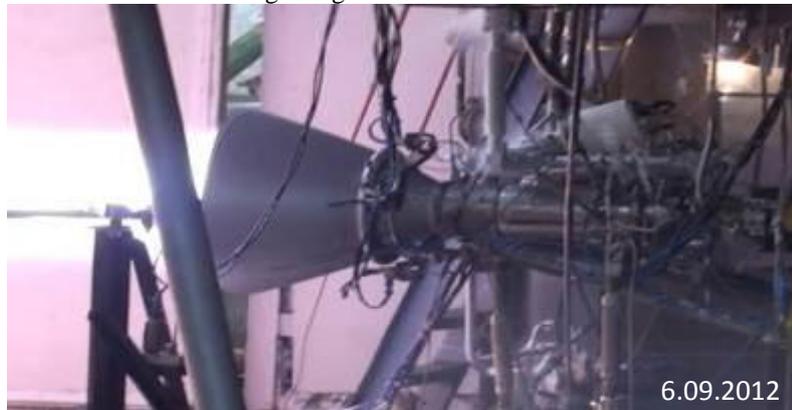


Figure 11. Firing test of the chamber in the frame of the UE2 unit

During firing tests, the following main tasks were successfully completed:

- operability of the chamber developed by KBKhA and AVIO was confirmed;
- experimental data on operation of the chamber in start-up, main and shutdown conditions were obtained;
- the chamber's operation cyclogram was confirmed;
- the chamber was tested with the wide range of fuel temperatures at the injector head inlet;
- the chamber's cooling ability was checked;
- combustion stability parameters of the chamber were evaluated.

The whole scope of works on the chamber's creation and fire testing was controlled by a AVIO and KBKhA team with immediate participation of ASI representatives.

#### *FTPA development*

The new fuel demonstrator turbopump has been designed for the typical objectives of a technological demonstrator (i.e. technology readiness improvement, technical feasibility of the overall project in view of its development to be performed in the subsequent phase), then not optimized for the use in flight.

A trade-off has been performed to identify the best TP architecture. The configuration chosen is a two stages pump (axial + radial) with one stage turbine, with balls bearings placed between pump and turbine.

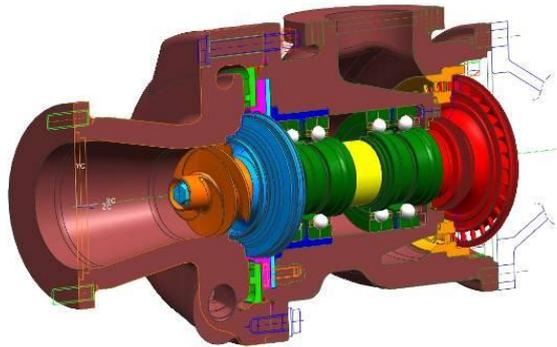


Figure 12. LM10-MIRA CH4 TP architecture

Advantages of this solution are to have a sub-critical spool, a simpler architecture and a balancing procedure at low speed. Pump is characterized by a low volumetric mass flow with an high pressure rise made up of only one centrifugal stage. The diffuser and the volute are both designed in order to minimize the pressure loss due to the very high dynamic pressure.

The turbine is one stage reaction and particular attention was focused on Manifold and the secondary flow optimization in order to increase the efficiency.

A new technology has been dedicated to manufacture in a short time with lower costs the more complex parts of the turbopump such as main housings (with pump volute), turbine manifold and impeller. These parts have been produced by additive manufacturing: Direct Metal Laser Sintering.

In order to validate the design solutions and to reduce the predicted performances accuracy testing activities of turbopump sub systems has been performed on pump (with relevant secondary circuit), turbine and bearing. In particular:

- turbine inlet stator test campaign in air;
- pump testing in water;
- bearing testing in LN2.

Experimental results, obtained from the FTPA subassemblies testing, were in line with analytical simulations validating that technical solutions, implemented in the design, have been dimensioned correctly.



Figure 12. AVIO Fuel TurboPump Assembly

#### *OTPA modification*

In the course of works, special attention was paid to design modernization of the oxidizer turbopump assembly (OTPA) and the igniter device.

During works with the OTPA (Figure 13), there was introduced a line for cooling of the OTPA bearings by LNG collected downstream the FTPA pump. This solution provided operability of the bearings in wide ranges and conditions of the demonstrator engine operation. Based on modernization results, a cycle of the OTPA acceptance tests was conducted in order to control the pump, turbine and rotor characteristics, tightness of the OTPA plug-type

connections and values of the flow rate through the floating rings of the interpropellant seal between the pump and the turbine. The tests proved a full compliance with the design documentation requirements.



Figure 13. KBKhA Oxidizer TurboPump Assembly

#### *Igniter modification*

Design activities conducted during modernization of the igniter device (Figure 14) provided reliable ignition of propellants in the chamber, taking into account requirements to the demonstrator's operation in the wide range of external conditions on which, among other things, the minimal propellants flow rate depends.



Figure 14. – The igniter device

Successful results of KBKhA components modernization were fully confirmed during the demonstrator's fire tests.

#### *The demonstrator's assembly*

The demonstrator's assembly was conducted at KBKhA's production plant since January 30 till March 28, 2014 in compliance with the applied documentation. At all stages, the assembly process was controlled by AVIO specialists, and all activities were agreed and registered in the engine's accompanying documentation.

The demonstrator's parts and assembly units were manufactured with application of technology and materials developed and used for the engines designed by KBKhA.

Executing the contract, KBKhA implemented a complex of design and technological works on modernization of the ПД0146U oxygen-hydrogen engine components to be used in the demonstrator. At KBKhA's stand and experimental facility, the feeding, ignition, control and regulation systems' components were autonomously tested, and the checks confirmed their operability in the frame of the oxygen-methane engine.

The demonstrator's scheme is shown in Figure 15. A gas discharge line was introduced downstream the OTPA and FTPA turbines in order to provide operation conditions of the oxygen-methane demonstrator. The line gives an opportunity to setup the LNG flow rate through the demonstrator and to conduct chemical analysis of the fuel.

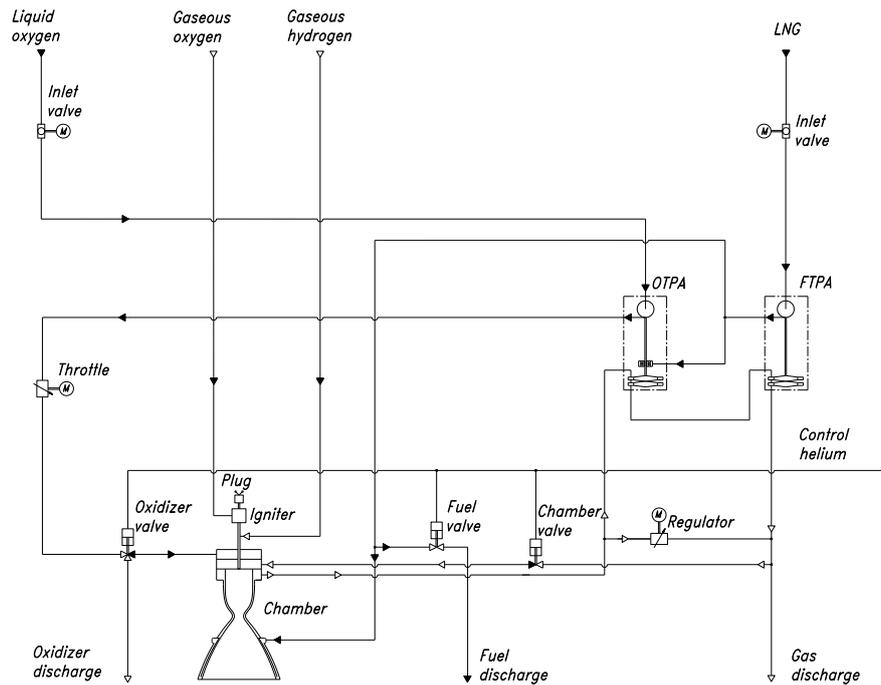


Figure 15. LM10-MIRA Demonstrator simplified scheme

The assembled demonstrator successfully passed all control procedures, including proof and leak tests. Control tests were guided by a workgroup of AVIO and KBKhA specialists in accordance with mutually approved programs and methods that were developed on the basis of the engine's technical specification. External view of the demonstrator is shown in Figure 16.



Figure 16. LM10-MIRA Demonstrator Assembly

Based on results of joint works on the demonstrator's integration, KBKhA, AVIO, ASI and ELV board decision has authorized demonstrator shipment to the test facility and mount it on the test stand.

### 3. The LM10-MIRA Demonstrator testing

The demonstrator test program included three start-up days and 11 fire tests with transition to the steady-state mode: the first day – 1 fire test with duration of 60 s, the second and the third days – 5 fire tests a day with duration of 60 s each. During the whole test series, total firing time reached the value of over 677 s.

The firing tests were aimed at solving the following basic tasks:

- functional check of the demonstrator's assembly;
- evaluation of the demonstrator's steady operation parameters;
- confirmation of possibility for the LOX – LNG expander cycle engine technical implementation;
- study of the demonstrator's LOX – LNG start-up with transition to the steady-state main mode;
- study of the demonstrator's operation during the main mode and shut-down;
- check of the demonstrator's start-up with vacuum conditions imitation;
- functional check of the chill-down, start-up and shut-down sequence;
- the Safety and Control System (CA3Y) algorithms testing;
- evaluation of the demonstrator's parameters;

External view of the demonstrator mounted on KBKhA test stand is shown in Figure 17.



Figure 17. LM10-MIRA Demonstrator on the test stand

Following logic of the test campaign was established:

In the first and the second test days, the engine settings parameters were adjusted and the engine steady-state mode has been achieved. In addition to this, during the second test day, a start-up in vacuum conditions was tested.

The aim of the third test day was to obtain maximum combustion chamber pressure values and nominal mixture ratio. The tests start up were conducted both: in atmospheric and vacuum conditions.

It is necessary to mention that a unique system of regular vacuum conditions imitation for engine start-up was specially developed for the demonstrator's firing tests on KBKhA test bench.

On the basis of requirements agreed between KBKhA and AVIO, the following main stand systems were used for testing:

- propellants supply system;
- safety and control system;
- parameter measurement and processing system;

- gas supply system;
- propellants utilization system;
- firefighting and other systems.

In the course of fire tests preparation, “cold” flow tests were successfully conducted. The tests pursued the following goals:

- the LOX feeding system operation check, the system’s hydrodynamic characteristics definition, setting the system for the assigned modes;
- the LNG feeding system operation check, verification of the LNG mass flow calculation method, setting the system for the assigned modes and other tasks;

Upon completion of the test preparation activities, an official Test Readiness Review was held.

During the TRR, KBKhA, AVIO, ELV and ASI specialists studied the results of “cold” tests, condition of the hardware, related documentation and the test task. Results of the meeting confirmed that the works complied with technical requirements. Participants of the meeting came to a conclusion that the stand systems and the demonstrator were ready for fire testing.

As it was mentioned before, the series of tests was conducted at KBKhA test stand in three startup days – on May 16, June 4 and June 24, 2014. Results of all fire tests showed that all requirements of the test task were fulfilled; the steady-state mode on the pressure inside the camber and the mixture ratio was provided; the engine start-up with imitation of vacuum conditions was checked.

The graphs given below reflect how the demonstrator’s main parameters with typical behavior changed during the Test №4. The qualitative nature of oxidizer (ДОФК) and fuel (ДГФК) pressure change in the injector head is shown in Figure 18. Oxidizer (ТОДД) and fuel (ТГДД) temperature change at the engine inlet, and oxidizer (РО) and fuel (РГ) mass flow rates are shown in Figure 19.

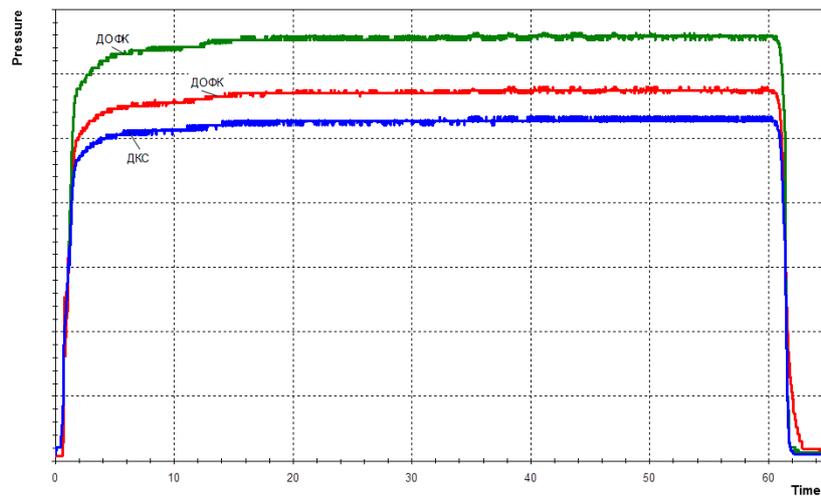


Figure 18. ДКС, ДОФК, ДГФК parameters behavior

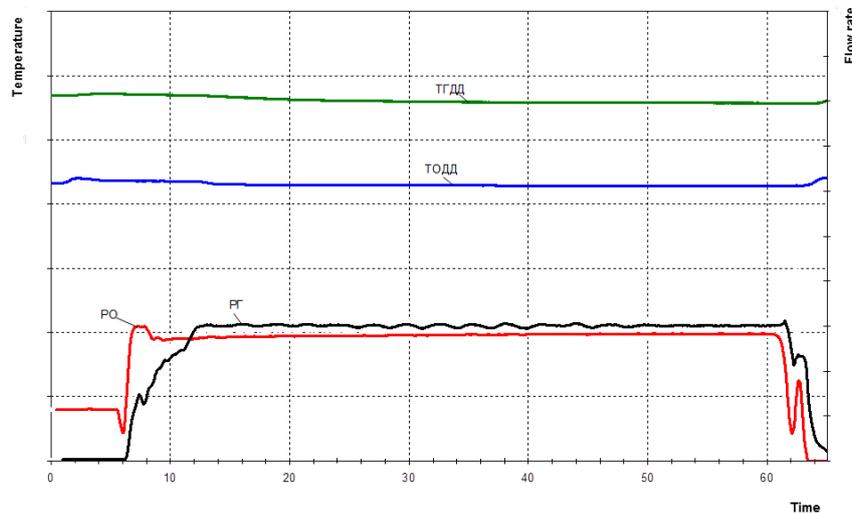


Figure 19. ТОДД, ТГДД, РО, РГ parameters behavior



Figure 20. LM10-MIRA Demonstrator engine fire test

After each start-up day, authorized specialists of KBKhA and AVIO conducted the demonstrator health monitoring including its components in accordance with requirements of the jointly developed specification. The health monitoring results were reflected in the minutes of technical meetings dedicated to the firing tests results and were a necessary condition for go-on decision on further testing.

After the third firing test day, based on results of all test campaign, Test Review Board has concluded the successful completion of the test activities.

#### 4. The demonstrator as basis of future Flight Engine

Activities on the Demonstrator gives the chance to verify the capability of the expander cycle to deliver the expected performance and to identify the main critical areas for the final development of the flight engine to be used for VEGA evolution Upper Stage application (chill down phases, ignition transients, restarts, combustion stability, thermal loads and cooling effectiveness).

The joint AVIO and KBKhA design team analyze the impact at system level of the developed subsystem at demonstrator level considering also constraints for the new upper stage.

Due to the stage geometrical constraints and the required performance, the new engine, LM10-MIRA, has been conceived with a deployable nozzle extension as preliminary choice (to be confirmed). Many solutions have been traded considering different turbopump architecture (single shaft, vs dual shaft), different logic of regulation (but always with the same assumption to have two valves to control the thrust level and the mixture ratio), different level of chamber pressure.

The required target performance and engine characteristics are resumed in the table below.

Into an expander cycle, the combustion chamber, apart from ensuring the specified thrust and  $I_{sp}$ , should provide for the required fuel temperature at the cooling line outlet, that determine the power given to turbines and consequently the pressure level that can be reached in the chamber.

|                                      |                |
|--------------------------------------|----------------|
| Propellants                          | LOX-LNG        |
| Schematic                            | Expander cycle |
| Thrust in vacuum, kN                 | 98.1           |
| Minimum $I_{sp}$ in vacuum, kgf-s/kg | 364            |
| Total flow rate (kg/s)               | 27.6           |
| Mixture ratio                        | 3.4            |
| Number of chambers                   | 1              |
| Thrust vector                        | $\pm 6^\circ$  |
| Max diameter, mm                     | 1300           |
| Max length, mm                       | 1900           |
| Weight, kg                           | < 295.5        |
| Number of re-starts                  | 5              |

Different cooling schemes have been considered in order to guarantee the required outlet temperature (not less than 550 K) and the minimum pressure drop. The alternatives considered has been showed in Fig 21 and are:

- cooling scheme with two consecutive contours;
- coolant supply from chamber head;
- coolant supply from the nozzle.

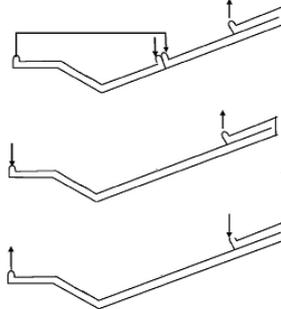


Figure 21. LM10- MIRA Flight Engine cooling schemes

In order to guarantee the required life in term of cycles and cumulated firing time, the maximum wall temperature has been limited to 800 K for the copper alloy region. The geometry of cooling channels that guarantee this minimum pressure drop, coping with given requirements it is the first one and this scheme has been selected for the architecture trade-off.

After the trade-off between different architectures for the SRR preparation, scheme presented in fig. 22 has been selected; the peculiarity of this cycle compared with the other options is that the FTPA turbine is fed with gas after the OTPA turbine (consecutive turbine feeding scheme); in addition a single by-pass before the turbine flow to control engine power is used.

This selected solution provides the best regulation capabilities to cover the design operational box, with lowest complexity; in addition this scheme presents major commonalities with the demonstrator engine.

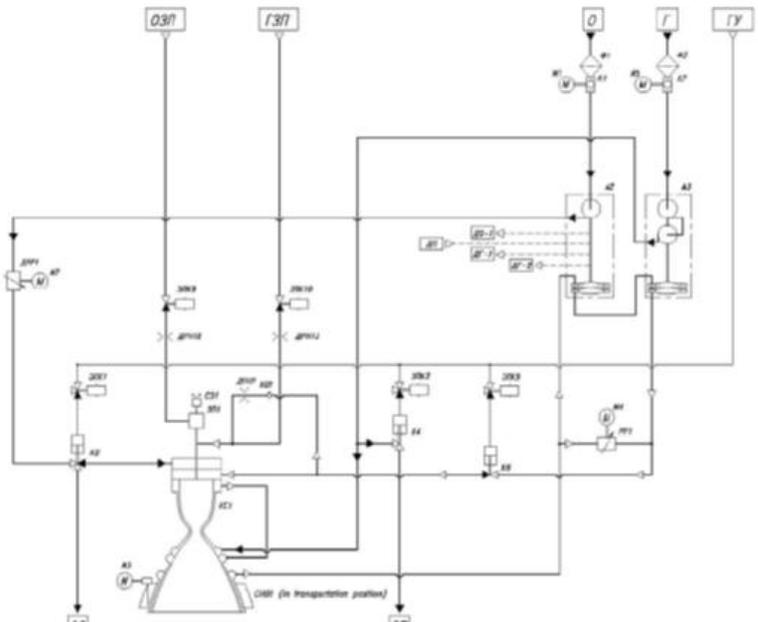


Figure 22. LM10-MIRA Flight Engine Functional Scheme

## 5. Conclusion

1. In 2007 – 2014, under the terms of ASI – Roskosmos inter-agency agreement, KBKhA and AVIO with participation of ELV successfully conducted the complex of works on creation of the LOX – LNG expander cycle demonstrator engine. The works included:

- design and manufacture of the demonstrator's components;
- autonomous “cold” and fire testing of the demonstrator's systems;
- manufacture of the demonstrator;
- preparation and checks of the stand systems;
- fire tests of the demonstrator.

2. During the demonstrator's fire tests, the following tasks were achieved:

- the demonstrator's operability and correctness of the selected cyclogram;
- total operation time of 677 s at 11 ignitions;
- possibility of multiple ignitions during one start-up day;
- stability of the combustion in the wide range of chamber pressure and mixture ratio operation processes;
- possibility of start-up in vacuum conditions.

3. During all the project phases, working together as a engine system responsible, Avio-KBKhA joint propulsion team has demonstrated the spirit of fruitful collaboration and the chance to apply the best approaches from both Russian and European space industries.

4. The results obtained and the experience gained during the Demonstrator Engine activities create the reliable technical basis to start a development activities linked to the LM10-MIRA Flight Engine as the possible evolutions of the Vega launch vehicle, powering the VEGA-E 3rd stage.

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