Optimization of Liquid Rocket propulsion system for Reusable Orbital Transfer Vehicle

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Abstract
The work is devoted to the investigation of possible ways to increase the efficiency of reusable orbital transfer vehicle (R-OTV) by using a multi-criteria optimization procedure of liquid rocket propulsion system (LRPS) design parameters. The “Federation” spacecraft is considered as an example payload of R-OTV for orbital transfer mathematical modeling, due to its known initial mass of 16,500 kg and other design parameters. Payload mass and specific cost of payload transfer are chosen as optimality criteria.

Multiple tasks are solved during the work: mathematical model and corresponding software for determining the optimal design parameters of R-OTV LRPS by mass and cost criteria are developed, R-OTV and LRPS calculation and optimization are conducted, the technical appearance of LRPS is designed.

Mathematical modeling is used to solve the presented problem. A developed mathematical model has a modular structure, in particular, it has modules for liquid rocket engine (LRE) mass calculating, OTV (Orbital Transfer Vehicle) mass calculating module, payload mass, design cost and manufacturing cost calculating modules for LRE and OTV and module for calculating the specific cost of payload transfer to target orbit. The intermediate result is used by LRPS project parameters design optimization module, then by technical appearance design module and LRPS units design module.

Multiple calculations are conducted with a developed mathematical model. Verification of the model is carried out by developing the technical appearance of real OTVLRPS. Several variants of LRPS for spacecraft “Federation” type OTV are designed for low lunar orbit, OTV parameters are compared with optimized LRPS and with existing LRPS.

Keywords: Liquid rocket engine, optimization, reusable orbital transfer vehicle.

Introduction
Traditionally, LRPS [1-5] design is based on LRE properties as a heat machine; this approach does not take into account close connection of the OTV main engine, which is the main unit of the system, with neighboring units and systems. When designing an optimal LRE, one should take into account the features of its functioning as part of the OTV. This approach will allow performing mission tasks with maximum efficiency.

The problem of reusability of the OTVLRPS in the environment of outer space arose at the dawn of the space age. At that time the primary task was to perform guaranteed launch of a spacecraft into a
target orbit, the spacecraft was launched only one at a time, and there was no need for multiple uses of OTV. In the early 1980s, the creation of OTV was seriously involved in the United States [6-9]. In 1987, the company "Martin Marietta" proposed a project of a reusable OTV [8]. Also, the OTV project was developed by the Massachusetts Institute of Technology in 1994 [9]. Several LRPS were developed on a competitive basis by Aerojet, Rocket dyne and Pratt&Whitney [10].

In Russia, two oxygen-hydrogen engines for R-OTV were developed. The first engine for OTV on oxygen-hydrogen propellant was the RD-56 developed by the Isaev’s Design Bureau (KBHM). A later modification of the RD-56 called KVD-1M had passed the full cycle of tests and is in normal operation as part of the last stage of the GSLV rocket (India) [11], [12]. The second engine for OTV on oxygen-hydrogen fuel is the RD-0146, developed in the 90s by Kosberg’s Design Bureau (KBKhA). The main difference from KVD-1M is that it uses expander-cycle of operation.

From the past year's projects analysis, it can be concluded that all projects of single-use and reusable oxygen-hydrogen OTV used as the main engine are expander cycle rocket engine.

Compared with R-OTV, OTV are quite expensive, but though well-developed and reliable. According to experts [13], [14], an R-OTV will have a right to exist if its application for launching spacecraft to various orbits (including GSO) would be more cost-effective than using an OTV. Achieving this economic efficiency is possible only with sufficiently large payload quantity of transportation to the target orbit. The value of this payload quantity was predicted from hundreds to thousands of tons for the entire duration of the transportation program.

The modern stage of space exploration is characterized by the large-scale implementation of targeted integrated programs for spacecraft removal using inter orbital transport vehicles. For the period from 1993 to 2006, with the help of OTV, more than 20 spacecraft a year were launched only at the GSO. Most of them were implemented using the ESC-A (Ariane 4 and 5) and Centaur (Atlas 2, 3, 5, and Delta 2, 3, 4) rocket stages[15].

Nowadays interest in exploitation the Moon and building a long-term orbital station and an inhabited station on its surface and its orbit has increased all over the world again. [16], [17]. To ensure this project, it will be necessary to regularly transport into the orbit of the Moon both large-sized station modules and transport supply ships. In total, to ensure such a program, according to forecasts, it will be necessary to transport about 435 tons annually and about 740 tons at the deployment stage. One of the ways to significantly reduce the cost of cargo delivery is the orbital spaceport Figure 1, the construction project of which is being discussed by large aerospace companies [18].

![Figure 1. An orbital spaceport in the S7 company's view.](image)

The task of building such a structure can be made easier by reusable rocket stages for low orbit transfer. [19]. The use of such systems can reduce the unit cost of breeding by 3 times or to 1,000 $ / kg and lower. The use of reusable spaceplane figure 2 to supply the orbital refueling station with propellant and launch payloads for subsequent transportation to the target orbit will allow cargo to be moved even to high-energy orbits using reusable OTV, even taking into account their substantial loss in the mass of payloads in comparison with OTV.
Method

It had been theoretically proved that, for the transportation of cargo in space, it is most expedient to create R-OTV with the maximum mass of output payload with the minimum cost of launching from a low earth orbit into the target orbit. To fulfill these conditions, a wide range of factors should be taken into account when designing LRPS: propellant type; features of the LRPS design; characteristic velocity costs for orbital transition for which the R-OTV is created; many economic indicators; mass characteristics; reliability characteristics.

To take into account such a wide list of factors, a mathematical model consisting of several modules is developed, the general structure of which is shown in Figure 3.

Since the main criteria for optimizing the parameters of an OTV LRPS are the mass of the payload and the specific cost of transfer the payload into the target orbit for the OTV LRPS. In addition to the general requirements for the rocket engines fuel to ensure that these criteria are met.

Figure 4 shows a dependence of OTV payload mass as a function of the characteristic velocity of transfer into the target orbit, calculated using a developed mathematical model. It follows from this graph that the use of oxygen-hydrogen fuel, despite all its disadvantages, will be most effective for the OTV LRPS.

When choosing an OTV LRPS design, preference in the scheme should be given to expander-cycle liquid rocket engines. The advantages of this scheme are mainly in increased reliability, operating life and higher economic indicators associated with the manufacturing of LRE and are described in detail in [20]. For R-OTV, one of the main requirements is high reliability and resource of LRPS with a small mass of construction, it is the expander-cycle LRE design that is most preferable in comparison with other schemes.

The details of developed mathematical model work are described in detail in PhD thesis [21].

To carry out the verification of the model, calculations are made and the design of the expander-cycle oxygen-hydrogen fuel rocket engine is formed using design parameters of the RD-0146 engine taken from sources [22], [23], [20]. A comparison of the results showed good convergence, the error was not more than 10%.

The main task of this work is the design of the technical appearance of R-OTV LRPS for “Federation” type space ship figure 5, with an initial mass of 16,500 kg, to bring the payload to low moon orbit.
Figure 3. R-OTV LRPS optimal parameters search mathematical model structure.
Figure 4. Comparison of the effectiveness of various propellant for the OTV LRPS, depending on mission energy requirements. The mass of OTV in the initial orbit is 22,000 kg.
Figure 5. “Federation” spaceship. The following parameters and assumptions are taken as the initial data:
- the value of the required characteristic velocity of the orbital transition is 4600 m / s;
- target orbit - low circumlunar orbit 110 km high;
- initial orbit - the height of 200 km, the inclination of the orbital plane of 51.6°;
- the diameter of fuel tanks and oxidizer is 4.1 m;

To facilitate the mode of operation of the turbo pump unit (TP) of hydrogen and provide a large resource and probability of failure-free operation, the rotational speed of the hydrogen TP rotor was set as a functional limitation - not more than 90000 rpm. To ensure the long-lasting durability of the nozzle and its resource, a functional limit was imposed on the maximum diameter of the nozzle outlet section equal to 2.2 m.

Results
The calculation results of the basic design parameters (BDP) of LRPS optimized for this R-OTV and their comparison with the LRP Son the basis of RD-0146 are shown in Table 1

Two variants of LRPS arrangement were considered - with one engine and annex tendable nozzle, and with four engines in an assembly. Obtained BDP allows to form the technical appearance of LRPS and calculate the design parameters of the propulsion system units.

In case of application of already developed LRE RD-0146, the mass of the payload transferred into the target orbit will be 9196 kg with 4 RD-0146 engines assembly and 2888 kg for one engine with an extendable nozzle, it is about 60% and 20% relatively optimized LRPS respectively. As a result, a significant increase in the R-OTV mass in the initial orbit will be required for the orbital transfer of spacecraft of a given mass for the OTV variants with RD-0146. Another disadvantage of the already developed RD-0146 is the high rotational speed of the rotor of the hydrogen turbopumps, 123000 rpm, 54% higher than in the optimized LRPS, which leads to a decrease in the reliability of the LRPS.

Main reasons for the low value of payload mass for R-OTV versions with RD-0146 are the low level of thrust-to-weight ratio (for the version with one RD-1046) and the large mass of the propulsion system with 4 RD-0146 (for the version with 4 RD-0146). According to the calculated data, it is clear that a higher specific impulse of an assembly of 4 engines (4523 m / s) is not enough to compensate an increased mass of the propulsion system (974 kg), even despite the level of thrust close to optimal (392.8 kN).
Table 1. Basic design parameters (BDP) of the liquid propellant rocket engine optimized for the OTV, transferring a 16,500 kg of payload on low lunar orbit.

| Parameter                                      | Value for OTV with optimized LRPS | Value for OTV with optimized LRPS with expandable 2.2 m diameter nozzle | Value for OTV with LRPS based on 4 RD-0146 | Value for OTV with LRPS based on RD-0146 with expandable 2.2 m diameter nozzle |
|------------------------------------------------|-----------------------------------|------------------------------------------------------------------------|--------------------------------------------|--------------------------------------------------------------------------------|
| Oxidizer excess ratio (oxidizer to fuel ratio) | 0.917 (7.27)                      | 0.923 (7.32)                                                            | 0.743 (5.89)                               | 0.743 (5.89)                                                                  |
| Nozzle area expansion ratio                    | 121                               | 157                                                                     | 200                                        | 600                                                                          |
| Combustion chamber pressure, Pa                | 58.8 $10^5$                       | 76 $10^5$                                                               | 80 $10^5$                                  | 80 $10^5$                                                                    |
| Propellant mass flow, kg / s                   | 85                                | 84.11                                                                   | 86.68                                      | 21.67                                                                        |
| Hydrogen temperature before TP, K              | 296                               | 260                                                                     | 300                                        | 300                                                                          |
| The rotational speed of hydrogen TP, rpm       | 70868                             | 79978                                                                   | 123000                                     | 123000                                                                       |
| Combustion chamber and nozzle cooling jacket pressure drop, Pa | 30 · $10^5$ | 25 · $10^5$                                                            | 30 · $10^5$                               | 30 · $10^5$                                                                 |
| Thrust in vacuum, kN                           | 374                               | 373                                                                     | 392.8                                      | 99.8                                                                         |
| Specific impulse in vacuum, m / s              | 4400                              | 4441                                                                    | 4532                                       | 4605                                                                         |
| Nozzle exit diameter, m                        | 2.2                               | 2.2                                                                     | 1.252                                      | 2.163                                                                        |
| LRPS reliability at each start                 | 0.993                             | 0.996                                                                   | 0.996                                      | 0.996                                                                        |
| LRPS maximum summary operation time, s         | 25530                             | 25210                                                                   | 24390                                      | 101400                                                                       |
| LRPS maximum on/off sequences during exploitation time | 114                              | 120                                                                     | 120                                        | 120                                                                          |
| Guaranteed on/off sequences                    | 1728                              | 2748                                                                    | 2748                                       | 2748                                                                         |
| Average ignition time, s                       | 224                               | 210                                                                     | 202.6                                      | 844.7                                                                        |
| Cost of 1 kg of payload transfer into target orbit excluding development costs, $ / kg | 11092                             | 11062                                                                   | 18425                                      | 61436                                                                        |
| Cost of 1 kg of payload transfer into target orbit taking into account development costs, $ / kg | 13353                             | 16560                                                                   | 20900                                      | 63728                                                                        |
| Total cargo traffic to target orbit for the entire time of R-OTV operation, kg | 913200                             | 957600                                                                   | 95760                                      | 95760                                                                        |
| Maximum payload mass transferred on the target orbit per launch, kg | 16750                             | 16510                                                                   | 9196                                       | 2888                                                                         |
| Mass of "dry" OTV, kg                         | 10570                             | 9930                                                                    | 11170                                      | 10610                                                                        |
| Propellant tanks mass, kg                      | 6443                              | 5946                                                                    | 6951                                       | 7579                                                                         |
Although, the fact that cost of researching and developing the RD-0146 engine can be disregarded, the specific cost of orbital transferring the R-OTV versions with RD-0146 (18428 $ / kg for 4 RD-0146 and 61436 $ / kg for single RD-0146) more than R-OTV with optimized LRPS (16560 $ / kg), even if we take into account the cost of its development.

The cost of developing an R-OTV is approximately equal for the variants with optimized LRPS and with 4 RD-0146, and for the variant with one RD-0146, it is 10% less, which is within the model error. The cost of development for an optimized LRPS and LRPS with 4 RD-0146 is about the same, and for the version with one RD-0146, is about 30% less.

The cost of manufacturing R-OTV with 4 RD-0146 is more than the other two options due to costs of manufacturing and installation of 4 engines, their integration into R-OTV design and increased dry
weight of R-OTV. An optimized LRPS manufacturing cost is higher than the cost of manufacturing RD-0146 due to the greater mass of the engine.

In case of using an assembly of 4 RD-0146, the mission may be completed only by increasing the sizes of R-OTV and propellant supply, which will entail an increase in developing and manufacturing costs of R-OTV due to increased dry mass, and require the use of a heavier-class rocket to transfer R-OTV into orbit.

Orbital transfers with a large value of characteristic velocity require a high energy efficiency of LRPS and reliable operation, despite the multiple on/off sequences and high level of heat and vibration protection for LRPS units. Entered functional limitations allowed to find BDP at which such level is reached - the rotational speed of hydrogen TP rotor was less than 80,000 rpm and required a temperature of hydrogen after the nozzle cooling jacket is 260 K.

Although, the relatively low heating temperature of hydrogen before of TP turbines, the pressure in the combustion chamber will be $76 \times 10^5$ Pa. This is due to the high value of the required fuel turbine efficiency 0.718. Obtaining such efficiency in a real construction may cause difficulties, in already existing hydrogen turbines with a lower mass flow efficiency level is 0.68-0.69. To eliminate these shortcomings, an optimal BDP are re-calculated with a new functional limitation - the efficiency of hydrogen TP turbine should not exceed 0.7.

![Optimal expander-cycle LRPS](image)

**Figure 6.** The technical appearance of “Federation” type R-OTV LRPS.
Figure 6 shows the technical appearance of LRPS with less heat-stressed parameters of hydraulic system power supply units. In this technical aspect, hydrogen TP turbines efficiency is 0.695, and rotational speed of its rotor is 70868 rpm. Such a decrease in required efficiency became possible due to an increase of hydrogen temperature after the cooling jacket, the hydrogen temperature is increased to 296 K, and higher value of turbine flow rate 7.64 kg/s. Combustion chamber hydrogen consumption is 10.11 kg/s, therefore, the excess hydrogen can either bypass turbines, bypass combustion chamber and nozzle cooling jacket, and immediately go to the combustion chamber from the first stage of the hydrogen pump. Of two optimized variants, less heat and vibro-stressed is more preferable; it more closely meets the reliability requirements due to the lower rotational speeds of the TP rotors. The advantages can also be attributed to the lower mass of such LRPS and lower cost of its development and production.

Disadvantages include an increased R-OTV mass on the initial orbit, up to 141,000 kg. Due to a decrease in the specific impulse from 4441 m/s to 4400 m/s, It happened due to a decreased combustion chamber pressure from 76⋅10^5 Pa up to 58.8⋅10^5 Pa. The specific cost of OTV low earth orbit launch is unchanged. Cost of R-OTV and LRE design and manufacturing decreased due to a decrease in the mass of the major LRE and a decrease in the level of the required failure-free operation probability of LRPS during each on/off, and consequently, the required number of tests.

Conclusion
Optimization of OTV LRPS parameters for a specific mission allows to increase the payload mass and reduce specific cost compared to the OTV with LRPS based on an already existing engine.

For the considered mission, the use of an optimized LRPS may increase payload mass 1.8 times and at the same time reduce the specific cost of mission 1.35 times compared to the non-optimized LRPS.

The developed technical appearance of OTV LRPS provides increased reliability, resource, simplicity, and efficiency of the design.

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