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Single-Shaft Turbopumps in Liquid Rocket Engines

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The article describes the evolution of design of main turbopump assemblies (TPA) in liquid rocket engines (LREs) developed by Chemical Automatics Design Bureau (KBKhA). The merits and limitations of single-shaft and double-shaft TPA configurations are analyzed. The major design distinctions of single shaft TPAs are:
– the execution of fuel and oxidizer pumps and turbine in a single unit;
– a mechanical link of pump rotors and the utilization of a single common turbine;
– identical rotation speeds of pump rotors.

Separate oxidizer and fuel TPAs with different rotation speeds and dedicated turbines are classified as double-shaft TPAs. Single-shaft and double-shaft TPA configurations implemented in the RD-120, SSME and RD-0146 engines are described. The criteria used in selecting single-shaft and double-shaft TPA configurations are provided.

Progress achieved in the area of hydrogen TPA development is demonstrated based on hydrogen TPAs developed at KBKhA at various times for two engines of similar thrust class: the RD-0410 nuclear rocket engine (NRE) and expander cycle-based RD-0146 liquid rocket engine. Key hydrogen TPA technologies, like powder metallurgy and techniques that ensure operability of rotors between 2nd and 3rd critical speeds, are described. Utilizing powder metallurgy, KBKhA was able to raise fracture speed of impellers in a hydrogen environment up to 930 m/sec and fracture speed of turbine rotors at normal temperature up to 810 m/sec. KBKhA-developed techniques to improve dynamic performance of rotors, including elastic damping rotor supports and rotor balancing in the operating speed range are described.

Improvement of the RL10 by utilizing a single-shaft TPA based on KBKhA's experience in development of single-shaft TPAs and Pratt & Whitney Rocketdyne's experience in constructing expander cycle engines are presented. Application of single-shaft TPAs with an oxidizer boost pump opens new possibilities for RL10 application while building on the successful RL10 track record. A single-shaft TPA provides the ability to increase engine thrust by 40% and reduce pump inlet pressure to the hydrogen and oxygen saturated vapor pressure. A configuration implementing a single-shaft TPA with an oxidizer boost pump is provided.

I. Introduction

Current LRE Performance, development time, and development and maintenance costs to a large extent are determined by the performance of and technologies utilized in turbopump assemblies. Modern hydrogen feed systems, including main and boost pump assemblies represent an important part of liquid space propulsion. The degree of TPA design sophistication and reliability has significant impact on engine performance. TPA efficiency drives important LRE performance parameters like chamber pressure. Anticavitation qualities of boost pumps determine hydrogen tank pressure and the ability to implement hydrogen feed to the engine inlet without tank pressurization. Durability of bearings and blades in a TPA turbine determines the frequency and cost of turnaround servicing of reusable engines.

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In LRE development, the TPA bears primary importance as it has the longest development cycle in all phases of engine construction: design, fabrication and development. The TPA is the highest loaded engine component with a large number of interrelated design elements. Complex design, high rotation speeds, and a direct link between TPA operating conditions and the processes occurring in the engine are the reason that defects attributable to the TPA represent a large proportion of the overall engine defects during development. Difficulties in eliminating defects occurring in the course of engine development are caused by the fact that processes occurring in a TPA are transient. For example, a TPA rotor performs from 500 to 2000 rotations per second and a defect related to the burning of hardware in oxygen environment develops within hundredths of a second. TPA construction represents a complex technical task during all phases of LRE development.

In the course of development of liquid rocket engines with staged combustion, specifically LOX-hydrogen LREs, significant progress was achieved in perfecting TPA design, performance and technologies. Construction of the LOX-hydrogen RD-0120 liquid rocket engine represented a new era in TPA technologies that ultimately became the foundation not only for development of TPAs for new LOX-hydrogen LREs but also for the newly-developed TPA for LOX-kerosene LREs.

Success in development of TPA technologies contributed to studies of potential improvement of performance of LREs already in service operation. The KBKhA-developed LOX-kerosene RD-0110 and Pratt & Whitney Rocketdyne-developed LOX-hydrogen RL10 LREs have been successfully operating for over 40 years on Soyuz and Delta and Atlas launch vehicles, respectively. As a replacement for an open cycle based RD-0110, KBKhA developed for the Soyuz-2 and Angara launch vehicles the RD-0124 – an engine that utilizes a more efficient stage combustion configuration. Pratt & Whitney Rocketdyne is currently developing RL10 performance improvements through application of a TPA jointly developed with KBKhA that represents a single-shaft configuration used in Russian LREs.

II. Turbopumps Developed by KBKhA

KBKhA has significant experience in developing TPAs for rocket engines for various applications. KBKhA constructed 86 TPAs, of which 69 represented main TPAs, 17 represented boost TPAs and 12 were liquid jet boost pumps (ejectors). The first TPAs were developed from 1954 to 1961 for an open cycle LRE (Table 1). The RD-0110 LRE developed during that time is still successfully operating as part of the 3rd stage on the Soyuz launch vehicle. Since 1961, KBKhA has been developing LREs utilizing highly efficient design with staged combustion of preburner gas. The RD-0210 (RD-0211) and RD-0213 engines implementing such design and operating on long-storage propellants are used on Proton’s 2nd and 3rd stages. In addition, a sustainer LOX-hydrogen LRE, the RD-0120, used on Energiya’s 2nd stage, LOX-kerosene RD-0124 intended for Soyuz-2 and Angara’s 2nd stage, and an advanced LOX-kerosene RD-0155 also utilize this design.

Table 1. KBKhA TPA Timeline.

NRE RD-0410
Main and Boost
Hydrogen TPA
1965

LRE RD-0120
Single-Shaft Main TPA,
Hydrogen and LOX Boost TPA
1976

LRE RD-0146
Hydrogen and LOX
Main and Boost TPA
1997

1954 – 1961	**1961 – 1977 years**	**1977 -2006 years**
Open Cycle LRE	Staged Combustion LRE	
Single-Shaft Main TPA		
Without Boost Pumps	Liquid Jet Boost Pumps (Ejectors)	Boost TPA

The evolution of LREs was accompanied by improvements in engine configuration and performance. LRE development can be divided into three phases:

- Phase 1 – construction of open cycle engines;
- Phase 2 – construction of staged combustion engines;
- Phase 3 – construction of LOX-hydrogen engines such as SSME (USA) and RD-0120 (Russia) utilizing staged combustion and high chamber pressure

Each subsequent phase in LRE development corresponds with a more complex design and higher strain levels in a TPA1. Comparison of performance among KBKhA-developed engines for the Soyuz, Soyuz-2 and Proton launch vehicles demonstrated that transitioning to staged combustion LREs leads to a dramatic rise in the parameters driving TPA strain levels. Pressure at the fuel pump exit increased by 80%, fuel pump impeller tip speed increased by 50%, turbine rotor tip speed – by 15%, and stress levels in blades – by 30%.

The main differences in TPA operating conditions between staged combustion cycle engines and open cycle engines are substantially higher pressure levels in pump and turbine cavities, reduced fuel propellant pressure at engine inlet and utilization of oxidizer working gas in the turbine. Ensuring strength and durability of TPA design became one of the major objectives in LRE development. Providing high efficiency and acceptable size and weight of the TPA required substantial (2 to 4-fold) increase in rotation speed. For fault-free operation of TPA pumps at high speeds and decreased propellant pressure levels at engine inlet required more complex feed systems. In addition to the TPA, ejectors, subsequently replaced by more efficient boost turbopump assemblies, were introduced in the feed systems. The close link between TPA operating conditions and operation of other engine components required a revised methodology in refining the design of the engine and TPA.

III. TPA for Rocket Engines Operating on Liquid Hydrogen

KBKhA developed five main and six boost TPAs for LREs and the main and boost hydrogen TPA for the RD-0410 NRE. The first hydrogen TPAs were developed at KBKhA in 1965 for the nuclear rocket engine RD-0410[1]. Basic design solutions and technologies in TPA construction for LOX-hydrogen engines were refined during the development of the RD-0120 engine and further augmented during the development of the LOX-hydrogen RD-0146 intended for advanced upper stage engines for Proton-M and Angara vehicles.

TPAs in LOX-Hydrogen LREs are characterized by substantially higher strain levels in the design. Compared to expander cycle engine TPAs, in the RD-0120, TPA impeller tip speed increased by 110%, turbine rotor tip speed increased by 40% and stress levels in turbine blades of advanced upper stage engines for Proton-M and Angara – by 170%.

In 40 years since the development of a hydrogen TPA for the nuclear RD-0410 rocket engine, significant progress was achieved in improving TPA performance. This is well illustrated by the comparison of flow and pressure parameters at the hydrogen pump exit in the RD-0410 NRE and RD-0146 LRE (Table 2).

Table 2. RD-0410 NRE and RD-0146 LRE Hydrogen TPA Parameters.

Parameter	NRE RD-0410	LRE RD-0146
Year Developed	1965	1997
Pump Flowrate, kg/sec	3.8	3.1
Pump Exit Pressure, MPA	224	265
Rotation Speed, RPM	65700	123000
Number of Pump Stages	3	2
Pump Impeller Tip Speed, m/sec	413	548
Number of Turbine Stages	1	2
Turbine Blade Strain, $n^2F_T \cdot 10^{-12}$ $(RPM)^2 \cdot mm^2$	13.8	27.9
Turbine Rotor Tip Speed, m/sec	468	452
Bearing Specific Speed ($D_{cp} \cdot n$), mm·RPM	$2.2 \cdot 10^6$	$>3 \cdot 10^6$
TPA weight, kg	35	16.5

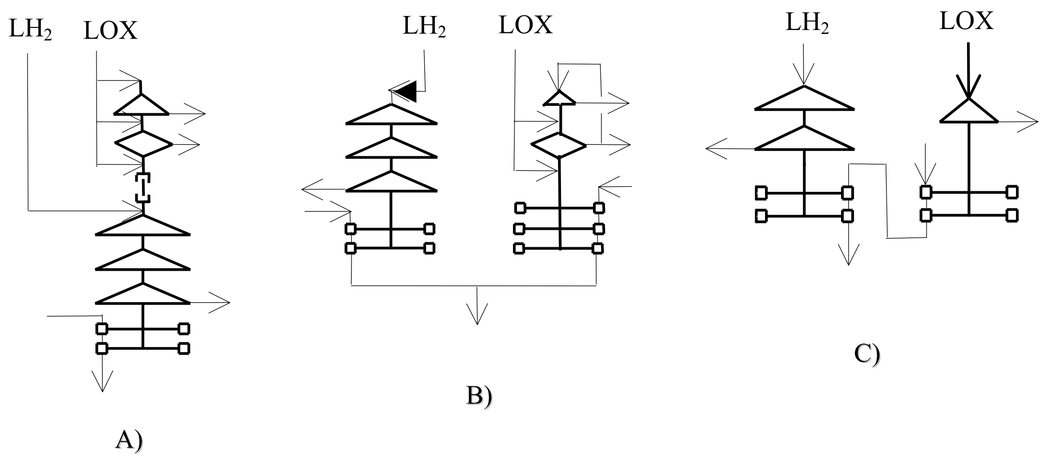
During the specified time, pressure created by one pump stage increased by 77%, impeller tip speed – by 33%, and stress levels in turbine blades - by 102%. The rotation speed increased twofold and TPA weight was reduced by 50%. Thus, modern hydrogen TPAs are characterized by high pump impeller and turbine blade strain and high bearing specific speed. To ensure operability of hydrogen TPAs with inherent high strain, new design solutions, materials and technology of fabrication were required. Technical solutions developed by KBKhA in the course of construction of TPA for the RD-0120 and RD-0146 engines served as a foundation for TPA design for current LOX-hydrogen engines. A number of these solutions are used also in TPAs of the newly-developed LOX-kerosene engine, RD-0124. These technical solutions and technologies represented the basis for the development of a single-shaft TPA for the RL10 engine.

IV. Single-Shaft TPA in Russian LREs

With the exception of RD-0146, in Russian LRE, main TPAs, including the TPA for the LOX-hydrogen RD-0120, are based on a single-shaft configuration. Engines of other countries (USA, France, Japan, and China) implement double-shaft design in their main TPAs. The KBKhA-developed LOX-hydrogen engine, RD-0146, is the first Russian expander cycle-based engine and the only Russian engine with a double-shaft TPA design.
Single-shaft TPAs have the following distinct features:

- fuel and oxidizer pump and turbine are executed in a single assembly;
- pumps have mechanical link of rotors and a single common turbine; and
- pump rotors have identical rotation speed.

Individual fuel and oxidizer TPAs with dedicated turbines and different pump speeds are classified as double-shaft. Figure 1 shows design configurations of the RD-0120 engine single-shaft TPA, and the SSME and RD-0146 engine double-shaft TPAs.



A – RD-0120 Engine Single-Shaft TPA
B – SSME Engine Double-Shaft TPA
C – RD-0146 Engine Double-Shaft TPA

Figure 1. Main TPA Configurations.

Advantages of single-shaft TPAs are:

- coordinated change in pump parameters at transient modes eliminating the need for onboard computer;
- simplicity of TPA design because oxidizer and hydrogen pumps share a common turbine; and
- simplicity of engine design because there is single preburner and associated single burn system, controls and externals.

The absence of a dedicated turbine in the oxidizer pump significantly simplifies the design and reduces pump development costs. Furthermore, rotor dynamic performance is improved and construction of a stiff (sub-critical) rotor becomes possible. Transient operation including start and shutdown essentially has no impact on rotor thrust balancing due to axial forces. Separation of liquid oxygen and turbine high-temperature working gas is prevented.

The main deficiency of a single-shaft TPA is the limited potential for optimizing pump and turbine performance. Hydrogen pump rotation speed is restricted by turbine blade strain and permissible rotation speed of LOX pump.

The major advantage of a double-shaft TPA in contrast to a single-shaft TPA is increased potential for optimization and forcing of LOX and hydrogen pump performance. However, this is offset by the deficiencies that are precluded in single-shaft TPA application.

The rotation speed of pumps, to a large extent, determines whether single-shaft or double-shaft configuration is selected for TPA. The selected rotation speed determines the efficiency of the TPA and of the overall engine. An increase of rotation speed within the established limits leads to increased efficiency of the hydrogen pump and turbine - the main elements in a TPA that define its efficiency, weight and size.

One of the criteria for rotation speed selection is pump specific speed 1(N – rotation speed, RPM; Q – volume flow rate, m^3/sec; ΔH – pumping head, m). For centrifugal pumps, specific speed N_s falls within substantially limited range of values from 40 to 130 (Figure 2). Specific speed N_s has an even more narrow range within which maximum pump efficiency is achieved.

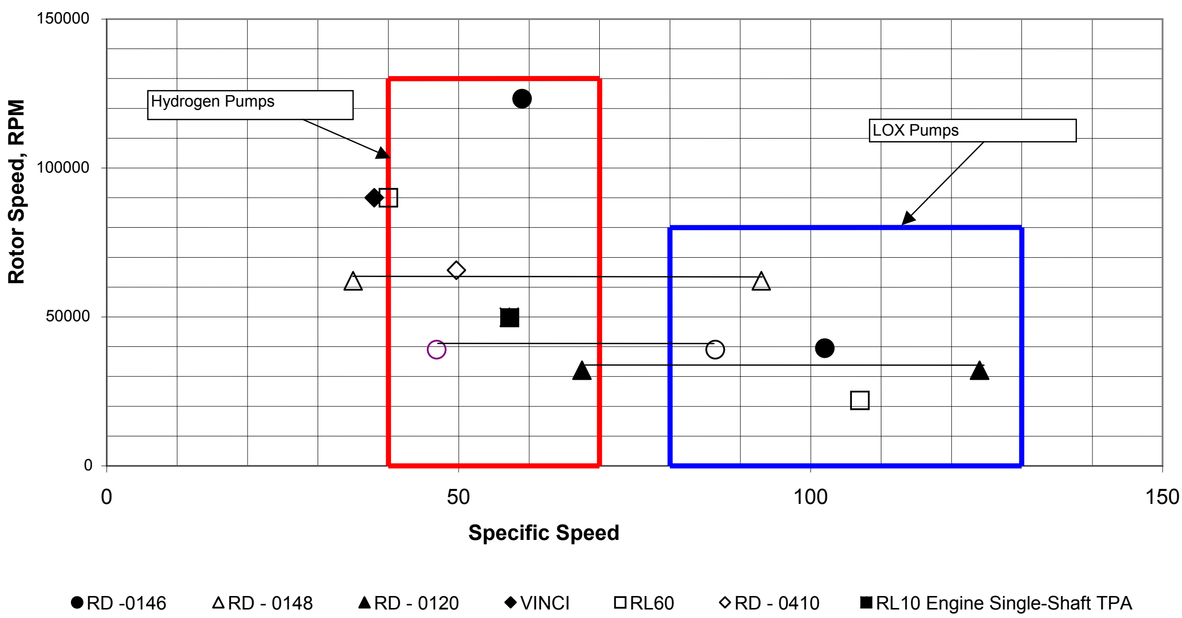


Figure 2. Pump Specific Speed.

Since hydrogen pump output exceeds LOX pump output by a factor of 3 to 4, TPA development is subject to ensuring hydrogen pump maximum efficiency, which is more difficult to achieve if TPA is constructed with a single-shaft configuration. Hydrogen pump head is 20 to 30 times higher than that of the LOX pump. As a result, pump speeds at which acceptable specific speed can be provided differ substantially. Identical pump speed levels can be generated by reducing head in hydrogen pump stages and lowering the flowrate through the LOX pump stage. This can be achieved if the hydrogen pump is designed with multiple stages and the LOX pump is multi-flow (with stages operating in parallel). Figure 3 demonstrates, based on the RD-0146 engine, rotation speeds for a double-shaft TPA configuration and for a single-shaft TPA with varying number of stages in hydrogen and LOX pumps.

Figure 3 demonstrates that in the RD-0146 LRE, which has expander cycle configuration, pump efficiency similar to that of a double-shaft TPA can be achieved only with substantially more complex design and increased weight and size. In this instance, a single-shaft TPA would have required a four-stage instead of two-stage hydrogen pump and with a LOX pump having bidirectional instead of single-direction inlet. Selecting a single-shaft and double-shaft TPA is not only the selection of pump and turbine rotation speed and performance but also a choice between an increased number of turbine stages in the double-shaft TPA configuration or an increased number of pump stages in the single-shaft TPA configuration.

Rotation speeds are further limited for both single-shaft and double-shaft TPA designs by:

- permissible stress levels in turbine blades;
- required boost pump head to provide fault-free operation of the main pumps; and
- bearing specific speed values.

In the double-shaft configuration, supply of working gas to the LOX and hydrogen TPA turbines (see Figure 1) can be executed sequentially (RD-0146 engine) or concurrently (SSME). In a single-shaft TPA, the entire working gas fed from a single preburner flows through the turbine. At a set speed for the hydrogen pump and gas pressure at the turbine exit in a single-shaft TPA, turbine blade stress levels will be greater than those in a double-shaft TPA configuration with concurrent or sequential gas feed to the turbines, if working gas is fed first to the TPA hydrogen turbine. Because blade stress levels due to centrifugal forces are proportional to the annular area of the turbine rotor exit and rotation speed squared, at identical turbine blade strain, single-shaft TPA rotation speed should be lower than that of the hydrogen pump in a double-shaft TPA configuration.

Studies of design and fabricated hardware demonstrated single- and double-shaft TPA configurations can be executed in a wide thrust range of staged combustion engines with preburner cycle. In expander cycle engines, with an increase in chamber pressure, the ability to use a single-shaft TPA becomes problematic. In the RD-0146 engine chamber pressure of 80 Bar is provided by a double-shaft TPA configuration at hydrogen pump speed three times higher than that of the LOX pump.

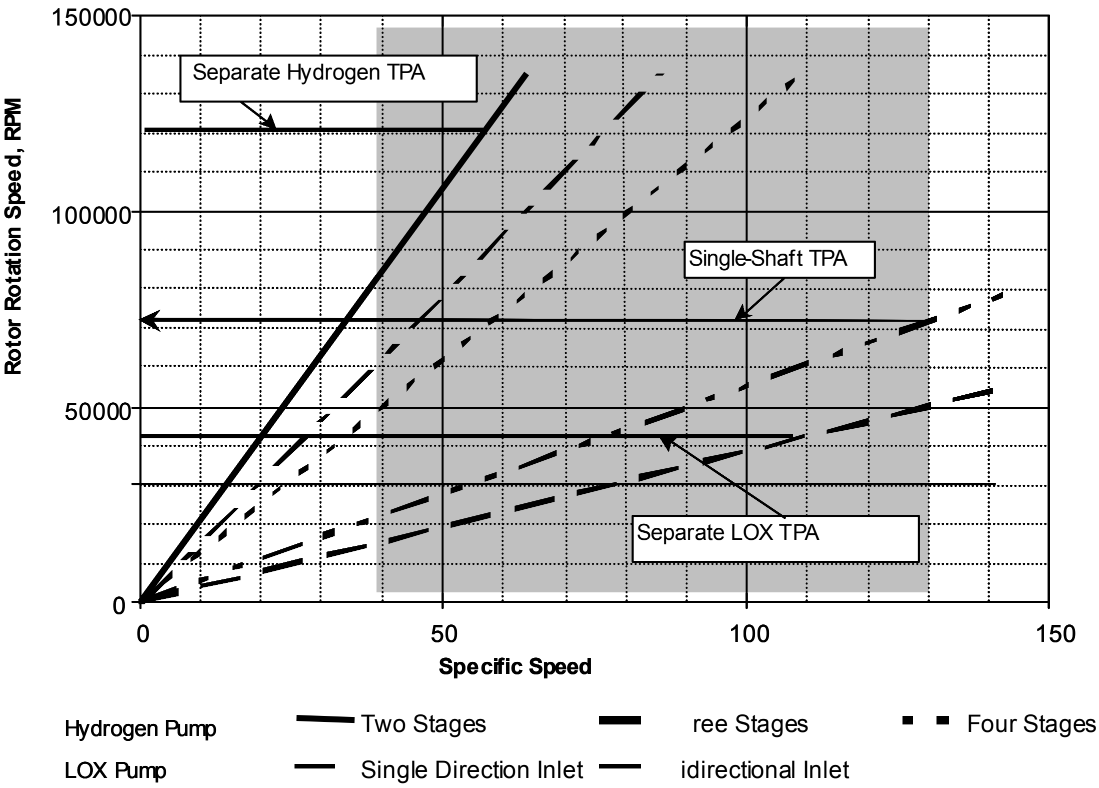


Figure 3. Single-Shaft and Double-Shaft TPA Rotation Speeds.

V. Hydrogen TPA Technology

Development of the most powerful Russian LOX-hydrogen LRE with staged combustion – the RD-0120 for the Energiya launch vehicle features a qualitatively new level of TPA performance and strain. Hydrogen TPAs are characterized by high strain levels in pump impellers and disks, and turbine rotor blades, rotor speed exceeding critical rotation speeds, high bearing specific speed, and deterioration of mechanical characteristics of design materials in the hydrogen environment.

During development of RD-0120 and RD-0146 LREs at KBKhA, main technical objectives for constructing TPAs for modern LOX-hydrogen LREs were accomplished through development of:

- Methodology for analytical and experimental studies to ensure the necessary life with consideration of hydrogen impact on materials structural strength;
- an experimental database of design materials performance in a hydrogen environment;
- the technology of fabricating powder parts made of nickel and titanium alloys;
- a system of processes for ensuring rotor operability;
- boost pumps operating on boiling hydrogen; and
- methodology for developing a TPA as part of a "cold" engine.

The use of blanks produced with powder metallurgy processes for high-stress parts as well as design and production techniques for ensuring rotor operation are the key technologies of modern hydrogen TPAs.

High strain levels in TPAs in combination with the deterioration of mechanical characteristics of design materials in a hydrogen environment required the development of new materials and technologies. KBKhA established a powder metallurgy production facility, which developed technologies for fabricating blanks for parts made of titanium and nickel alloys. KBKhA has been using powder materials in TPA parts for 30 years[2]. During this period, 16 powder material parts such as pump impellers and vanes, turbine rotors and vanes, shafts, and fasteners have been refined. Fabrication was developed for turbine and pump parts with flowpath shaping in the process of powder blanks fabrication. Technology for electrical discharge machining of blades together with disk and rotor tip shroud and turbine vanes was refined and implemented. Figure 4 shows RD-0120 single-shaft TPA hydrogen pump rotors and the RD-0146 TPA hydrogen pump rotor, in which all parts are made of powder blanks. Implementation of powder metallurgy technology ensured that the fracture speed for titanium alloy impellers was as high as 930 m/sec in a hydrogen environment, and that of a nickel alloy turbine rotor was as high as 810 m/sec at normal temperatures.

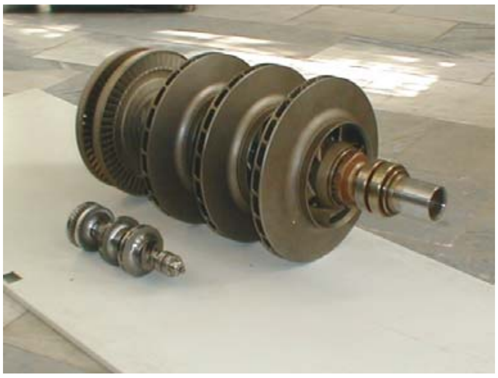


Figure 4. RD-0120 and RD-0146 Engine Hydrogen Pump Rotors.

Figure 5. RD-0120 Engine Rotor on Spin Balance Test Stand.

Use of a flexible rotor operating between 2nd and 3rd critical speeds required a number of new technical solutions aimed at ensuring dynamic stability. To provide TPA operability, KBKhA developed:

- methodology for analytical and experimental refinement of dynamic characteristics of rotors;
- rotor design, technology of fabrication and assembly[3];
- design of elastic supports with high damping capability[4];
- methodology for rotor high-speed balancing within operating speed range[5];
- rotor high-speed balancing rig[6]; and
- simple and highly effective system of automatic rotor axial thrust balance control[7];and
- designs for bearings with specific speeds in excess of $3{\cdot}10^6$.

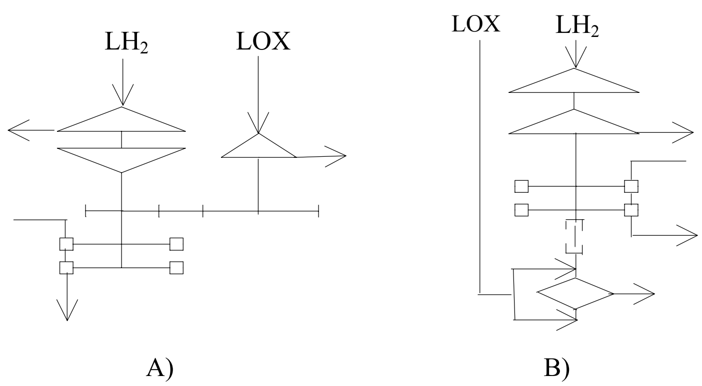
Major TPA technologies developed by KBKhA in the course of designing RD-0120 and RD-0146 engines served as the basis for developing turbopumps for modern LOX-hydrogen engines. These technologies served as the foundation for a single-shaft TPA that was being developed for the RL10 engine.

VI. Improvement of the RL10 Engine via incorporation of a Single-Shaft TPA

In 1963 the RL10, which was the first LOX-hydrogen LRE developed by Pratt & Whitney Rocketdyne featuring an expander cycle, entered service operation. This engine is still successfully operated on upper stages of Delta and Atlas launch vehicles. Thereafter, expander cycle engines were being developed in Russia (RD-0146 LRE) and in France (Vinci LRE). It is must be noted that in 1965, KBKhA developed a NRE, wherein heating of hydrogen supplied to turbine was performed with a nuclear reactor through an expander cycle. In RD-0120 and SSME LREs heating of hydrogen supplied to the turbine of hydrogen boost TPAs was also executed without a preburner.

Excellent reliability of expander cycle engines resulting from low TPA strain levels and the absence of preburner and related burn systems, controls and externals is their main advantage for upper stage applications. Low temperature and an evenly distributed working gas temperature field at the turbine inlet, low thermal shock at start and shutdown, and low thermal gradient in its design elements at steady-state operation ensure high turbine reliability in the environment of multiple firings and prolonged operation. That is why the RL10, which over 40 years of its operation was subjected to 65% thrust increase, has such prolonged life cycle.

The RL10 TPA has an intermediate position between a single-shaft and double-shaft TPA. Similar to a single-shaft configuration, in this TPA, hydrogen and LOX pumps and turbine are made as a single unit, pumps have one common turbine, and rotors are mechanically linked with a gear reduction unit (Figure 6A). Similar to a double-shaft TPA, as a result of gear reduction unit, the rotation speed of hydrogen pump rotor in RL10 TPA is higher than that of a LOX pump. Consequently, the RL10 engine TPA embodies the advantages of both the single-shaft and double shaft TPA configurations. However, introduction of high-speed gear reduction unit imposes restrictions of engine life and thrust increase. A TPA with a single-shaft configuration, which was constructed utilizing KBKhA's expertise in single-shaft TPA design and Pratt &Whitney's experience in this engine's operation over a course of many years, provides RL10 with increased operating margins (Figure 6B).



A – TPA with Gear Reduction Unit;   B – Single-Shaft TPA

Figure 6. RL10 TPA Configurations.

Application of a single-shaft TPA with a LOX boost pump (Figure 7) creates new possibilities for RL10 application while preserving to the maximum extent possible previous operating experience. A single-shaft TPA enables an increase of RL10 thrust by up to an additional 40% (Figure 8). Together with the MB-XX, the RL10 engine with a single-shaft TPA covers a 50 to 270 kN thrust range. The axial stage in the main TPA, and the boost TPA in the LOX feed line provide high anti-cavitation qualities in the hydrogen and LOX feed lines, respectively. A single-shaft TPA with a LOX boost TPA provides reduction in pump inlet pressure to the pressure of saturated vapors of hydrogen and oxygen. The LOX boost TPA is made based on standard KBKhA design8. This design was implemented by KBKhA in 13 boost TPAs, including the LOX boost TPAs for RD-0124, RD-0155, RD-0146 and RL60 engines. These boost TPAs provided excellent reliability since they contained only one rotating part – the inducer with hydraulic turbine rotor installed along its external diameter.

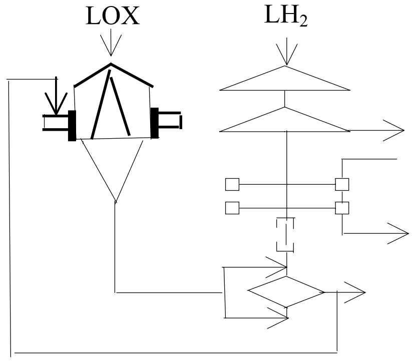


Figure 7. Single-Shaft TPA with LOX Boost Pump

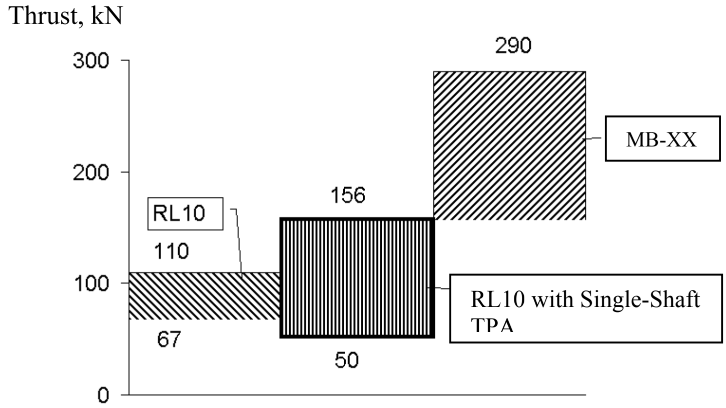


Figure 8. Thrust of RL10 with Single-Shaft TPA.

The single-shaft TPA for the RL10 engine (Figure 9) implements all major technical solutions used in the single-shaft TPA in the RD-0120 and the hydrogen TPA in the RD-0146. The hydrogen pump has a double-stage design and LOX pump has a bidirectional inlet. Double-stage turbine rotors are installed on the hydrogen pump shaft. Pump shafts are linked with a spline spring. Operating rotation speeds of rotors are below critical rotation speeds of the LOX pump and between the 2nd and 3rd critical speeds of the hydrogen pump rotor. Pump rotors are balanced in the entire rotation speed range, including critical speed values. Tandem ball bearings in hydrogen pump rotor are placed in elastic damping supports. The hydrogen pump utilizes efficient automatic axial thrust balance control of the rotor. The hydrogen pump and turbine utilize cost-effective seals with self-aligning rings[9]. Hydrogen pump impellers, inducer, guide vane, and shaft are fabricated from powder blanks. Traditionally for KBKhA, pump and turbine housing parts are stainless steel castings.

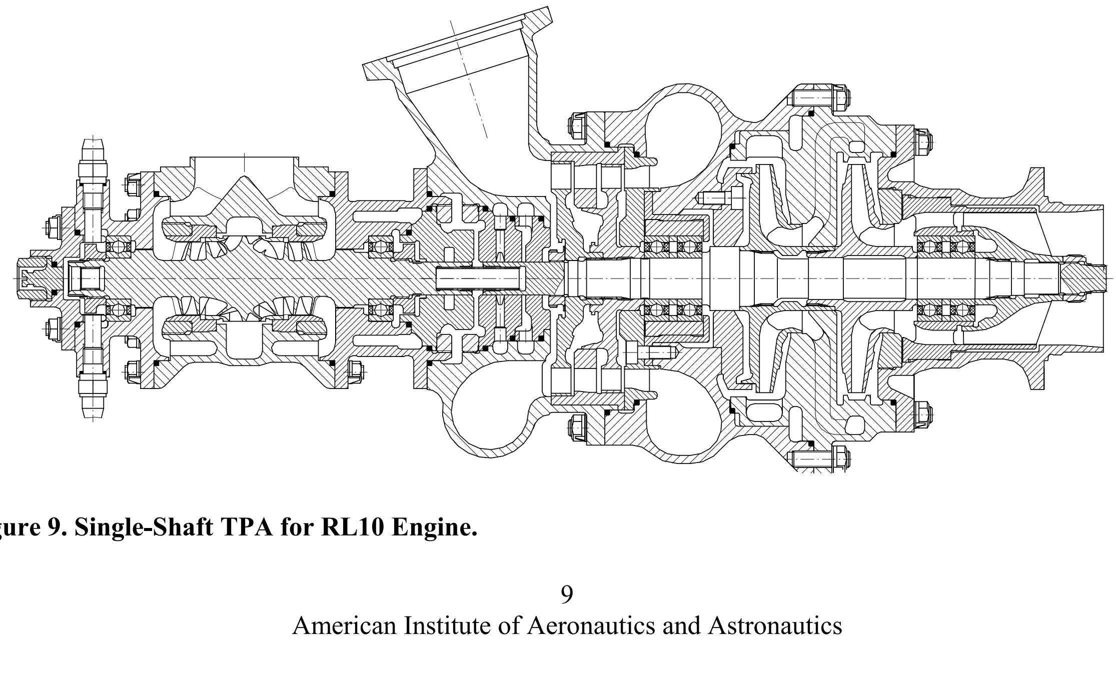


Figure 9. Single-Shaft TPA for RL10 Engine.

Pratt & Whitney Rocketdyne and KBKhA have been conducting studies for the practical application of a single-shaft TPA in the RL10 engine. Design and manufacturing documentation has been developed and conceptual and detail design reviews have been held allowing for successful modification of a single-shaft TPA in the existing RL10 engine. Fabrication of long production cycle parts (castings and powder parts) has already started. Delivery to Pratt & Whitney Rocketdyne of the first TPA specimen is scheduled for October 2006. Prior to delivery, TPA component-level development testing will be completed utilizing KBKhA-established practices.

This methodology of by-element refinement of performance and operability includes the following types of TPA testing:

- structural pressure proof testing of housings
- structural spin testing of rotor parts
- system-level tests of rotor assembly through spinning in operating speed range
- determination of pump output performance in the entire range of engine operation, including start and shutdown
- determination of pump cavitation characteristics in a wide range of flowrate values
- determination of thrust balance device performance
- determination of turbine performance in a wide engine operating range, including start and shutdown.

These tests increase confidence in the ability to provide the required functional and operating performance of each design element in the TPA operating conditions and permit establishment of performance margins for these elements before TPA is delivered and engine-level tested. Another important advantage of component-level testing is the ability to define operating limits and further refine necessary improvements prior to delivery of a final fabricated TPA and for subsequent TPA forcing.

Activities on the single-shaft TPA for the RL10 were preceded by joint collaboration, which had been successfully implemented over the course of 10 years, on the construction of main LOX TPA and LOX and hydrogen boost pumps10. Experience of collaborative work between Pratt & Whitney Rocketdyne and KBKhA demonstrates that there are no restrictions imposed on an inter-governmental level to successful cooperation. In the course of joint activities, Pratt & Whitney Rocketdyne and KBKhA were able to build a strong business relationship ensuring successful construction of a single-shaft TPA for the RL10 engine.

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