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Single Shaft Turbopump Expands Capabilities of Upper Stage Liquid Propulsion

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I. Abstract

The world's first liquid oxygen-liquid hydrogen closed expander cycle engine, the RL10, was created over 44 years ago by Pratt & Whitney Rocketdyne and has been a successful mainstay for the upper stages of US launch vehicles ever since. Continuous improvements over the years have increased the thrust of this engine to over 140%. Recent component development activity includes the cooperative design, manufacture, and test of a single shaft turbopump to replace the geared RL10 turbopumps. In combination with a liquid oxygen boost pump and a combustion chamber being developed by PWR, the single shaft turbopump can increase the RL10 thrust to 35,000 pounds while maintaining reliability, fail-safe operation, and ease of multiple restarts of the expander cycle design. The requirements for the single shaft turbopump are based on Pratt & Whitney Rocketdyne system expertise and US engine development experience, while the actual pump design and its features were based on KBKhA's more than 60 years experience in designing single shaft turbopump. This paper will review various turbopump development approaches and potential opportunities to support engines in the RL10 thrust class. The advantages of both the current geared and the single shaft turbopump configurations will be discussed. This paper will review various configurations for the single shaft turbopump including the alternate positioning of the turbine and pumps as well as various configurations for individual turbine and pump elements. The single shaft turbopump was designed for multiple thrust levels. The development methodology for a pump capable of operating at multiple thrust levels will be discussed. Some of the conceptual designs which were evaluated will be reviewed. KBKhAs approach to developing turbomachinery also addresses rotordynamics methodologies, assembly, maintainability, and off nominal operating conditions. KBKhA's integrated element, subcomponent, component, and turbopump assembly development approach will be discussed. This integrated approach continues through assembly and test of the integrated single shaft turbopump assembly using liquid hydrogen and liquid oxygen. Representative results from tests at each level will be reviewed as well as the plans for testing in the US. The test results will be reviewed to provide an understanding of KBKhA's component development approach. Finally, the potential application of the single shaft turbopumps to increase the thrust of RL10 engines at various thrust levels will be reviewed.

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II. Introduction

Engine cycles with pre-burners operate with high-temperature turbine gas that reduces the service life and limits the number of engine firings. Turbines for expander cycle engines operate in a more benign environment: low turbine inlet temperatures, uniform turbine inlet temperature profiles, low thermal shocks during start and shut down transients. All of these factors are all beneficial to extending the operating life and the multiple restart capability.

Engines without pre-burners have lower temperature difference between the fluids in adjacently located turbine and pumps. This reduces thermal stresses on the turbine rotors and on the pump and turbine housings. The reliability of the expander cycle engines is provided by the simplicity of design and by the low structural and thermal load on the turbine. The low temperature of gas in the gas manifolds and turbines, and the small amount of gas residual in the flow path ensure minimal heat flow from the turbine to the pumps after engine cutoff, which favorably affects the engine restarts.

The simplicity of the expander cycle engine is partly a result of the absence of a pre-burner and as well as the simplicity of the ignition system, the valves and controls, and plumbing compared to that of staged combustion cycles. These special features and the associated high reliability of the expander cycle engines helps explain the long life of the RL10 engine, which is still being used on the upper stages of the Atlas -5 and Delta -4 rockets. The merits of the RL10 expander cycle have established the baseline for upper stage engines such as the LE-5 (Japan), RD0146 (Russia), and the Vinci (France).

III. Turbopump feed system cycles for liquid propellant rocket engines

In the 1960's, the USSR pursued development of Liquid Propellant Rocket Engines (LPREs) in a different direction than other countries. In the USSR, all engines, oxygen-hydrogen engines included, used closed cycle staged combustion. The rest of the world, however, was developing engines using open cycle configurations. The SSME engine in the shuttle is an exception to this rule and uses a staged combustion cycle. In Russia, engines were developed with a single-shaft driving the pumps for both propellants while other countries used separate turbines and drive shafts for each propellant. A significant Oxygen-Hydrogen expander cycle engines exception was the Pratt-Whitney Rocketdyne RL10 engine that used a turbopump system with a single turbine driving both pumps. Interestingly, KBKhA developed the RD0146 engine with two separate turbopumps, one for each propellant, as compared to their prior history of using a single turbine to drive both pumps.

Single-shaft turbopumps have the following distinctive special features:

the pumps of fuel and oxidizer and turbine are combined in a common pump set;
the pumps are mechanical connected to one common turbine;
the rotors of pumps have identical operating speeds.

When separate turbopumps are used for each propellant, each turbopump has its own turbine and the operating speed is selected based on the propellant properties. Examples of the two-shaft configurations are illustrated in figure 1 which shows the schematics for the SSME and RD0146 engines. The same figure shows the configuration of the single-shaft Turbopump assembly (TPA) forRD0120 engine.

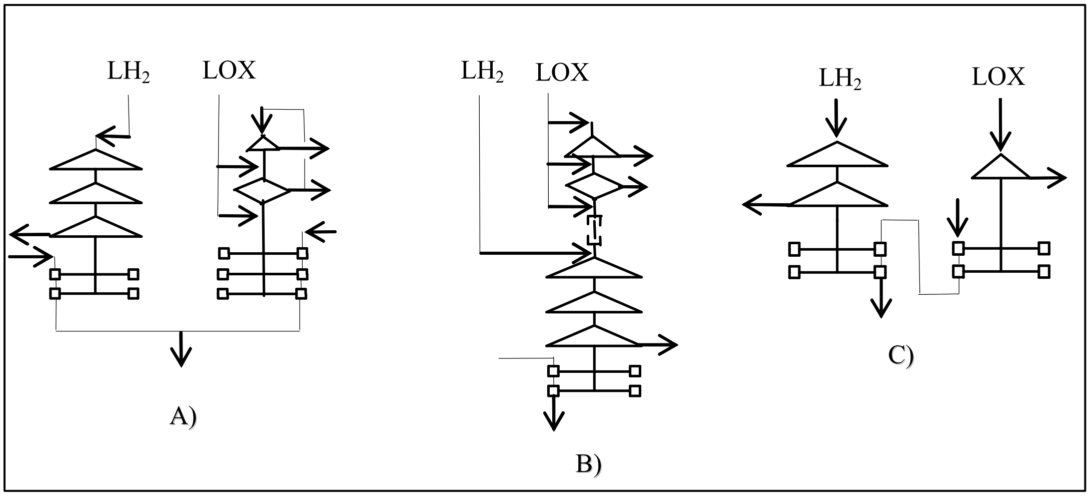
Merits of the single-shaft TPA:

The mixture ratio mechanical controlled and does not require an on-board computer to maintain mixture ratio during transient operations;

the pump design is simplified since the oxygen and hydrogen pumps have a common turbine;

the engine design is simplified since there is one turbine with one turbine drive system, requiring only one pre-burner, control and manifold system.

The elimination of the turbine for the oxygen pump substantially simplifies the design and fabrication and decreases costs for pump validation. The dynamic characteristics of the rotor are improved as it is possible to use a sub critical rotor design. The separation of liquid oxygen and high-temperature turbine gas is facilitated. The main disadvantage of a single-shaft TPA is the limitations to optimizing the pump and turbine operating parameters for each propellant as both pumps are constrained to operate at a common speed.



A – Two shaft cycle of SSME TPA
B – Single shaft cycle of RD0120 TPA
C – Two shaft cycle of RD0146 TPA
Figure 1. TPA cycles

The primary advantage of two-shaft TPAs compared to single-shaft TPAs is that it is possible to optimize the parameters of oxygen and hydrogen pumps for the physical characteristics of corresponding propellants. The single-shaft and two-shaft TPA are each designed based on the speeds required for the main pumps. An increase in the speed within certain limits gives an increase in the efficiency of the hydrogen pump and turbine, which are the high power elements of the TPA and determine unit's efficiency, mass and overall size. The speed of the single-shaft TPA limits the power-speed coefficient of the oxygen pump and the turbine blade load. In a two-shaft configuration, the speed of hydrogen TPA is faster, and oxygen TPA slower than speed of single-shaft TPA. With all other conditions being equal (engine thrust, pressure in the chamber), the permissible turbine blade load of the hydrogen TPA at high speed enables a reduction of work for the turbine as compared to the parallel gas flow required in a 2 shaft (and 2 turbine) configuration.

The studies of designs and the actual performance of these designs shows, depending on the chamber operating pressures, both single-shaft and two-shaft configuration TPAs in expander cycle engines have potential. In the RD0146 engine, where the chamber pressure is80 bars, the two-shaft configuration TPA is appropriate. The hydrogen TPA speed is123000 rpm, which is three times the speed of oxygen TPA.

The RL10 uses gears to synchronize the two pumps in a common gearbox driven by one turbine and could be considered an intermediate configuration compared to the single shaft or separate turbopump configurations. The RL10 pumps have a common turbine with a mechanical connection (either directly or through a gear set) to both pump rotors, (figure 2). As in the two-shaft configuration, the hydrogen pump can operate at a higher speed than the oxygen pump. Consequently the RL10 configuration has the efficiency of a two shaft configuration and the mixture ratio control of a single shaft configuration. However, the highly loaded gear train can become the limiting factor and influence the service life of engine.

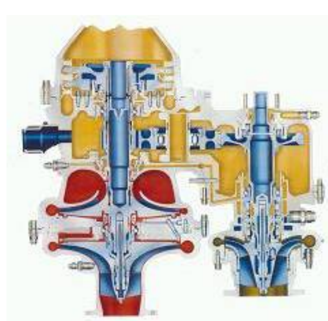


Figure 2. RL10B-2 Engine Propellant Flow Schematic

IV. RL10 engine single shaft turbopump

During the last 10 years PWR and KBKhA have cooperated in TPA programs. One of the latest joint activities between PWR and KBKhA was a single shaft turbopump designed for the RL10 engine. This RL10 SSTP was designed, fabricated, and tested to provide increased reliability and extend the operating range of the RL10 engine.

Pratt-Whitney Rocketdyne and KBKhA developed an SSTP for the RL10 in order to further expand the thrust range while ensuring robust reliability and retaining the mature operating history and the advantages of the expander cycle configuration. The work between PWR and KBKhA included creation and evaluation of various SSTP configurations designed for the current thrust levels as well as increased thrust turbomachinery for future thrust growth capability.

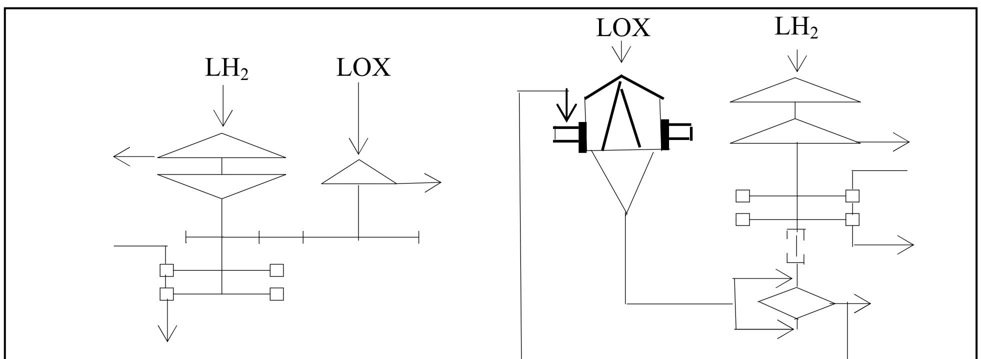
The application of this SSTP in combination with a liquid oxygen boost pump (figure 3) and with specific chamber modifications will make it possible to increase the thrust of the RL10 engine to 35,000 pounds. Furthermore, replacing the gear train with a common drive shaft eliminates the gear loads, wear, and vibration, increasing the service life and providing enhanced restart capability.

Use of the SSTP in the RL10 it ensures:

- Increased robustness and continued reliability;
- Increase in operating margin and flexibility of application;
- Increased thrust to 35,000 pounds;
- Robust throttling allowing operation from 11,000 pounds to 35,000 pounds;
- Possibility of reduced tank pressurization.

The high anti-cavitation qualities of the axial inducer in front of the first centrifugal stage in the hydrogen pump allows the pump to function properly even with saturated vapor pressures at the pump inlet. The high oxygen pump speed requires an oxygen boost pump to ensure adequate cavitation margin. To maintain reliability while adding a boost pump, the KBKhA LOX boost pump contains only one rotating component, the inducer, which includes a tip turbine at its OD. KBKhA has created a whole series of booster pumps including oxygen booster pumps for the oxygen-kerosene engines RD0124, RD0155 and for the oxygen-hydrogen engine RD0146[3] based on this proven, mature, design concept.

Development of the single-shaft TPA for the RL10 engine was based on KBKhA's experience developing single-shaft TPAs for the RD0120 oxygen-hydrogen engine and the oxygen-kerosene RD0110, RD0124, and RD0155 engines. The development of the single-shaft TPA also drew upon KBKhA's experience developing the hydrogen - oxygen TPA for the RD0146[4] engine.



A – Turbopump with reduction gear unit; B – single shaft TPA with oxygen boost pump

Figure 3. Cycles of RL10 TPAs

Based on its experience with the expander cycle engines as well as other US engines, Pratt-Whitney Rocketdyne provided the design, reliability and safety requirements, as well as the physical and functional interfaces. PWR also provided the test requirement for the turbopump assembly. The turbopump internal design of the SSTP, including the inter-propellant seal, the configuration pumps and turbine, the rotordynamic characteristics, the damping supports, the dynamic and static seals, were all based on KBKhA's 60 years of experience developing single-shaft TPA for various liquid rocket engines. The use of KBKhA's experience ensured reliability and operability as well as the required performance characteristics. KBKhA's experience established a disciplined validation and verification approach including specific tests of the pumps and turbine and the high-frequency rotordynamics tests. Additionally, simple assembly that prevents incorrect assembly and ensures maintainability and robust margins for operation under nonstandard conditions result from more than 60 years of experience.

Various configurations were evaluated prior to selecting the final configuration of the SSTP. The alternate configurations included options with and without boost pumps, as well as, alternative arrangements of the turbine and pumps on the rotor stack. The best configuration was selected based the requirements provided by Pratt & Whitney Rocketdyne, which include the desire to make as few changes to the existing engine interfaces as possible. Additionally the SSTP was designed to maximize commonality between the 22,000 pound thrust and 35,000 pound thrust variants.

Two basic concepts for a single-shaft TPA were subjected to detailed analysis. The first concept was based on the RD0120 SSTP configuration. The second concept was focused to maximize compatibility with the existing RL10. The optimum speed for each concept was established and the performance, inlet stability, operating margins, control criteria, and rotordynamic characteristics established.

Like the RD0120 engine, the first RL10 SSTP concept has both oxygen and hydrogen boost pumps. The rotor stack has the turbine on one end, the hydrogen pump in the middle, and the LOX pump on the other end. The RL10 SSTP would not require a 3rd hydrogen stage like the RD0120 or the additional LOX kick stage required for the RD0120 pre-burner. By locating the LOX pump away from the turbine, the turbine gas temperature is not transferred to the LOX pump and a standard IPS package can be used to separate the two pumps. The use of two boost pumps as employed in the RD0120 did not match the heritage RL10 configuration and reduced the compatibility with the current vehicles. Furthermore, including two booster pumps into the existing RL10 engine would require significant changes to the engine configuration.

The second concept was focused on avoiding the need for a hydrogen boost pump, while maintaining the hydrogen pump axial inlet. Two configurations of the hydrogen pump were analyzed – one with a centrifugal first stage and one with an axial stage before the centrifugal stages. The hydrogen pump with a centrifugal first stage could not ensure proper operation at the required inlet pressure so the configuration with the axial step before first centrifugal stage was used. This configuration required KBKhA to place the turbine between the oxygen and hydrogen pumps in the rotor stack. In an expander cycle engine the low operating temperature of the turbine makes it possible to use this configuration without excessive impacts on the LOX pump. For the RL10, the option with a hydrogen pump with an axial inlet stage without a boost pump was selected.

KBKhA then conducted further trades to optimize the elements of the selected configuration. In particular the choice between a single-stage and a two stage turbines was examined. The two stage turbine configuration was selected since the single-stage turbine did not provide the required efficiency.

The need to operate at multiple power levels further complicated the selection of the pump and turbine configurations. A configuration was established to meet the two engine configurations (22,000 lb thrust and 35,000 lb thrust) by replacing the turbine inlet vanes and rotors. This insured minimal changes between configurations and maintained maximum commonality in components, while minimizing hardware and test requirements.

TPA development at KBKhA is an integrated approach of design, manufacturing and testing of turbopump parts' and turbopump assemblies from the beginning of design. This approach includes testing at each stage of component development, design modification and verification at each phase, and closed loop feedback from test results to the manufactured hardware. This approach is applied beginning from parts testing, through the tests of the major components-- bench testing the turbine with a simulation gas and fluid testing of each pump and the thrust balance device, as well as the verification of the rotor sealing, bearing support systems and damping systems. The rotor dynamics are tested at all operational levels, including maximal and critical rotor speeds. This integrated approach extends to the test and feedback into the design and all the modifications made until the TPA is assembled and tested with propellants ($LOX/LH_2/GH_2$). The final modifications are introduced only after all the tests of the integrated TPA have been completed.

The RL10 SSTP has three hydrogen pump stages: the axial first stage and centrifugal second and third stages. The oxygen pump has a double-sided inlet design which has been proven on previous KBKhA engines. The oxygen pump operates at sub critical speeds. The Hydrogen pump rotor (Figure 6) speed operates between the second and the third critical rotor speeds. The torque transfer from hydrogen pump shaft to oxygen pump shaft occurs through a spline with a light weight connecting shaft. This is a typical approach for single shaft TPAs developed at KBKhA. The duplex ball bearings for the hydrogen pump are mounted into elastic damper supports with corrugated elastic element[i, ii] (Figure 7). The pump rotors are balanced across the full range of rotor speeds, including the critical rotor speeds of hydrogen pump[iii]. KBKhA has used this rotordynamic verification approach for more than 30 years. Additionally, the thrust balance system used in pump[iv, v] and the floating ring seals used in the hydrogen pump and turbine[vi] are thoroughly grounded in KBKhAs prior engine experience.

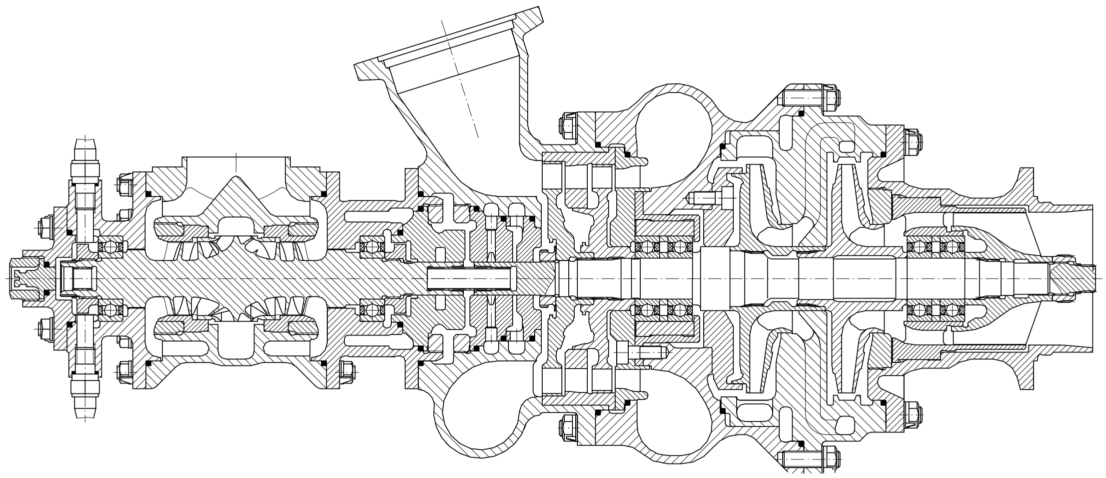


Figure 4. Layout of RL10 engine single shaft TPA

Figure 5. Single shaft TPA of RL10 engine

Figure 6. Rotor of single shaft turbopump hydrogen pump

Figure 7. Plate-type corrugated elastic elements

The impellers, inducer and hydrogen pump manifolds (Figure 8) are made of powdered titanium alloy and the pump shaft of powdered nickel alloy. The shrouded impeller channels in the hydrogen pump are fabricated net shape with no further machining required. KBKhA has been using net shape powder metal fabrication since development of the RD0120 engine more than 30 years ago. Subsequently powdered metallurgical parts have been used in the TPAs for the RD0146 and RD0124 engines. The bladed turbine disks (Figure 6) of the single shaft TPA have a shroud, but are produced net shape. The turbine wheel blades are manufactured by EDM. This approach has also been applied by KBKhA for more than 30 years[vii]. All of the main housings of the pumps and turbines are cast from stainless steel.

Figure 8. Hydrogen pump parts of powder alloy (inducer, first and second stage impellers, distributor blank)

The RD0146 was also developed by KBKhA and has the same thrust as the current RL10 engine. The RD0146 engine, developed for the upper stage of the Proton and Angara launch vehicles, has two TPAs: one for LOX and one for LH_2. Each propellant has a boost pump. The RL10 SSTP and the RD0146 hydrogen TPA both have two turbine stages and two centrifugal hydrogen pump stages. The RL10 SSTP has considerable margins, which ensures reliability for the operating requirements.

V. Turbopump development testing approaches

In the course of LPRE development different approaches to turbopump testing can be used:
TPA testing with propellants
Testing of TPA elements with simulation fluids.
Testing of TPA parts with simulation fluids, followed by testing of assembled TPA with propellants.

As various countries began their development of liquid propellant rocket engines they invariably began with gas generator cycle engines. The relative simplicity of gas generator cycle ensures high reliability and relatively low development costs. Gas generator engine components operate relatively independent from each other facilitating their component development. The turbopump challenges when starting and stopping a gas generator cycle are simpler than for a closed cycle engine. These features make it possible to develop the TPA separately from the engine. Since the independent turbopump testing can use working fluids other than cryogenic propellants it is easier to guarantee TPA operability before testing at the engine level.

Component testing TPAs using simulation working fluids does not determine the limits of the component's operability, nor does it identify the characteristics that limit its operability. The required engine life and number of starts can be established through the study and improvement of each individual component part. Component testing using simulation fluids provides information that can not be obtained during engine testing at a fraction of the cost of testing in cryogenic fluids.

During the transition to staged combustion engine cycles, independent testing of the TPA with propellants before the engine test was deemed expensive and inefficient and it did not guarantee the TPA operability at engine level. For successful component level testing, many tests are required which leads to significant development costs and an increase in schedule.

TPA tests with simulation fluids are performed in two phases. The first phase defines the pump and turbine characteristics and safety margins of highly loaded TPA parts. In the second phase, there is a detailed study of characteristics of each element to identify and improve as necessary to achieve the engine level requirements.

Sub-component testing of the TPA using the simulation is conducted in parallel with preparation of the components for the test engine. The second stage of component testing is conducted in parallel with the hot fire testing of the engine. Additional tests, brought about by engine test results, are also conducted in the second stage. Furthermore, the improvements incorporated during the first phase of testing are validated along with changes identified during engine testing. Conducting the component parts development in parallel with the engine testing reduces the schedule and cost of engine development.

During component testing on simulation fluids, the characteristics of component parts are evaluated over a wide range to establish the performance margins and sensitivities of each element in the design and to determine ways to optimize the resulting engine as a whole.

VI. Component Testing of Single Shaft TPA parts

For the RL10 SSTP, the conventional KBKhA approach of testing the TPA sub components with simulation fluids was used. The scope of testing for this SSTP was established based on the requirements set by PWR. These tests of SSTP included:

– Pressure proof testing of the structural housings;
– Leak tests of the structural housings;
– Strength tests of rotor parts by spin testing, including to testing to failure;
– Rotordynamic testing of the assembled rotor across the full operating range;
– Verification of the performance of the oxygen and hydrogen pumps over the full range of engine operation, including start up and shut down;
– Definition of cavitation characteristics of oxygen and hydrogen pumps;
– Definition of hydrogen pump Thrust balance device characteristics;
– Definition of hydrogen pump axial stage characteristics;
– Definition of turbine characteristics over the full range engine operation modes, including the start up and shut down;
– Pressure definition in pump and turbine flow paths;
– Tests of bearings and seals.

The performance of hydrogen pump and turbine as well as the thrust balance device characteristic are given in Figures 9-11 based on the component testing performed. The pump and turbine characteristics were determined by the tests with simulation fluids in specialized test rigs. Pump testing was performed on water and the turbine was tested using heated air.

The pump characteristics were determined over a wide range of operating modes from negative flow rate to negative head (Figure 9). Turbine characteristics (Figure 10) were determined over a wide range of Parsons' number (Isentropic Velocity Ratio U/C_0) with several values for the expansion ratio. The wide range of pump and turbine characteristics includes all operation modes at engine level, including start up and shut down.

Characteristic of the hydrogen pump thrust balance device (Figure 11) was defined during the pump testing in the same rig in which the power and cavitation characteristics of the pump were defined. This rig has a mechanism for changing the axial thrust acting on the rotor[viii]. The thrust balance device characteristic obtained experimentally shows the axial forces at all operation levels, including engine start up and shut down, acting on the rotor bearings.

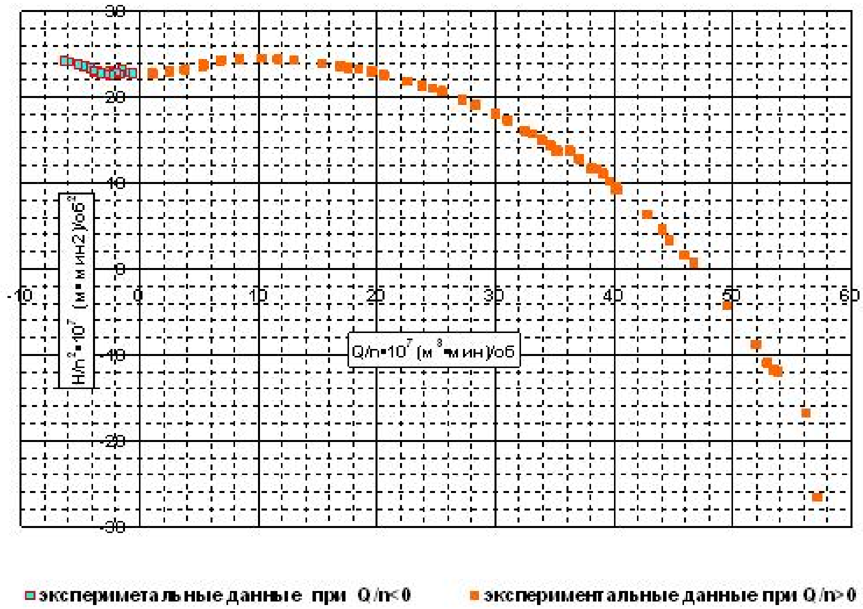


Figure 9. Hydrogen pump normalized head characteristic Test data

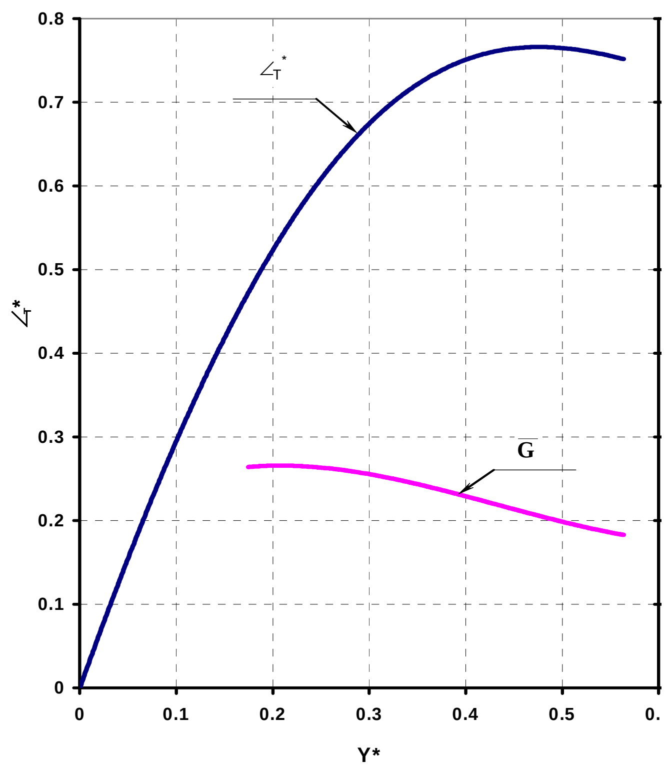


Figure 10. Turbine characteristics (efficiency, normalized flow)

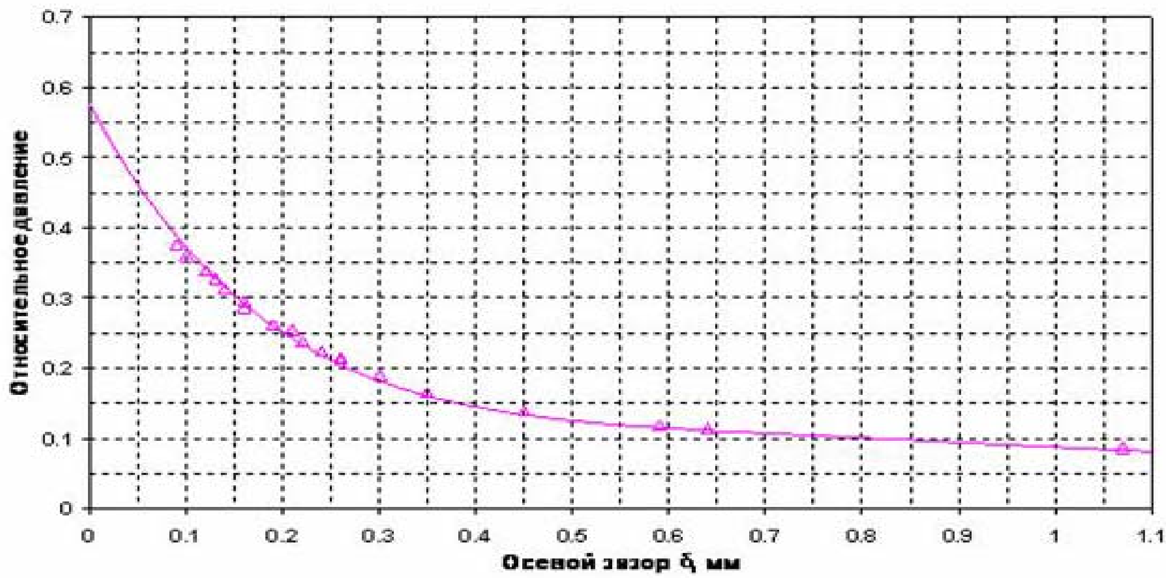


Figure 11. Hydrogen pump TBD characteristic pressure vs. axial clearance

Rotordynamic testing of the assembled rotor over the full operating speed range is a mandatory requirement in KBKhA's development methodology[ix]. The dynamic rotor characteristics defined during this testing are the Eigen frequencies, the amplitudes of rotor radial oscillations, dynamic loads on the support, and the rotor axial displacement. The rotor is modified as required based on test results and the requirements for subsequent parts' manufacture and rotor assembly are updated as required.

High-frequency tests and high-frequency rotor balancing are conducted with the elastic damper elements on the supports, which are used in the assembled TPA. This work is performed on the balancing stand (figure 12) in a special installation, created for the rotor [15]. The SSTP rotor passed the complete cycle of tests. The high-frequency tests of the rotor, which confirms the stability of the dynamic characteristics of rotor after disassembly and repeated assembly, were carried out after high-frequency balancing. High-frequency balancing and subsequent high-frequency tests of rotor confirmed the correctness of the rotor design of rotor, rotor mounts and the quality of the components and rotor assembly.

Each rotor for PWR was subject to high-frequency balancing and rotordynamic testing, confirming its manufacturing and assembly quality.

The main factors driving high-frequency balancing and rotordynamic testing include:

– Increase turbopump life and reliability by increasing bearing durability through reduced dynamic loads;

– Increase turbine and pump efficiencies by decreasing the clearances in the seals resulting from the the decrease in the amplitude of rotor radial oscillations;

– Effective control of rotor manufacture and assembly quality;

– Increase in engine reliability due to the decreased vibration loads of turbopump acting on its components, ducts and other engine components.

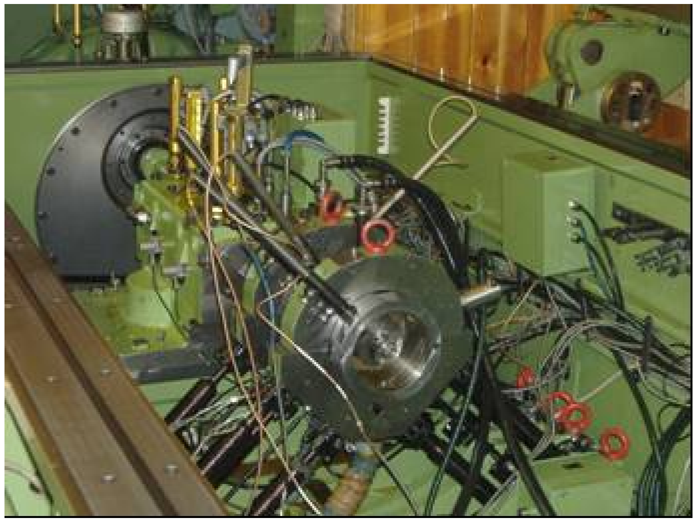


Figure 12. SSTP Hydrogen pump at Rotordynamic Test Bench

The effectiveness of high speed balancing of the SSTP rotor compared to the balancing at low speed is shown in Figure 13. After balancing at full operational rotor speeds the dynamic support loads and amplitudes of rotor radial oscillations were 4-5 times less than the typical low speed balancing.

The equipment and tooling used for high speed balancing and the high speed balancing procedure are expensive, but the benefits achieved through high speed balancing completely justifies the costs through decreased turbopump and engine test cost. The confirmation of the benefit of high speed balancing is the RD0120 engine developed by KBKhA for the Energia-Buran. The high speed balancing together with the plate elastic support dampers eliminated all rotor related defects relating to balance and rotor dynamics in all engine testing phases.

The testing of SSTP parts with simulation fluids also confirmed the manufacturing quality, the characteristics required by SOW and confidence to use the SSTP during the testing at the engine level.

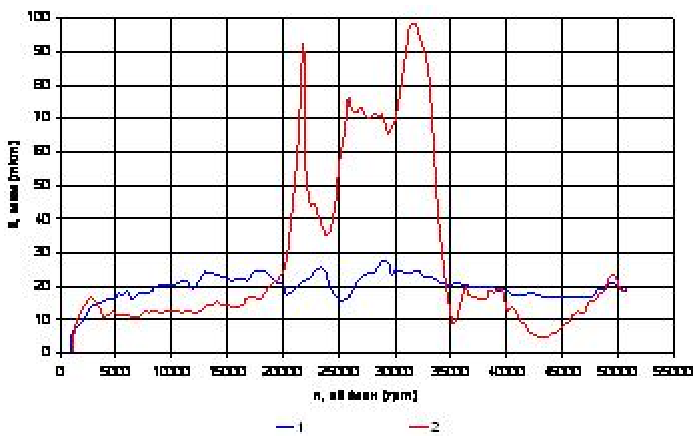


Figure 13. Dynamic support loads and amplitudes of hydrogen pump rotor radial oscillations
1 – after balancing at operational rotor speeds, 2 – at the balancing at low rotor speeds

VII. Sub-component testing of single shaft LOX-H_2 TPA

PWR and KBKhA performed testing of the SSTP at KBKhA with LOX and hydrogen to demonstrate the SSTP performance and validate KBKhAs' development methodology. One of the goals of these tests was to allow PWR to evaluate the test stand integration, test flow schematic and the preparatory activities performed before and after the tests.

A stand interface rig was designed and fabricated to facilitate the SSTP component tests in cryogenic propellants. The SSTP was mounted on this rig and the rig was then mounted on the test stand (Figure 14). The tests were performed on the same KBKhA test stand (Figure 15) used for the RD0146 engine tests. The SSTP tests were performed 2.5 years from the beginning of the SSTP design program.

Test objectives included:

– Verification of SSTP operation at full power, part power, and during start and shut down transients;

– Verification of operation across a wide range of flow rates (hydrogen ± 20%, LOX -20% to +25%);

– Confirmation of repeatable behavior through start, steady state, and transient operations.

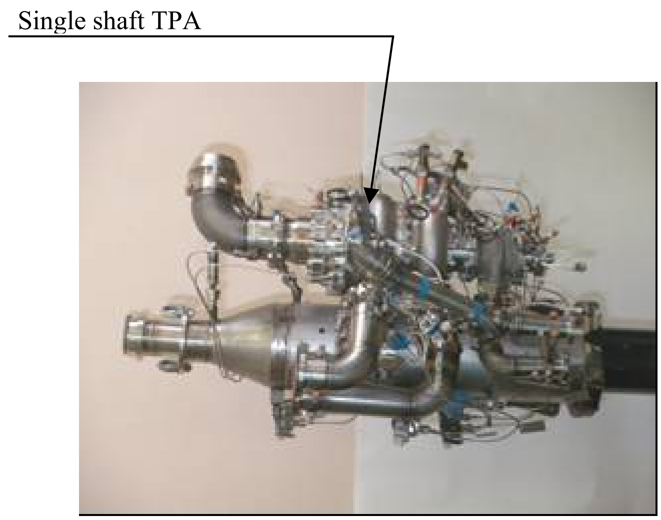


Figure 14. Rig for SSTP Testing

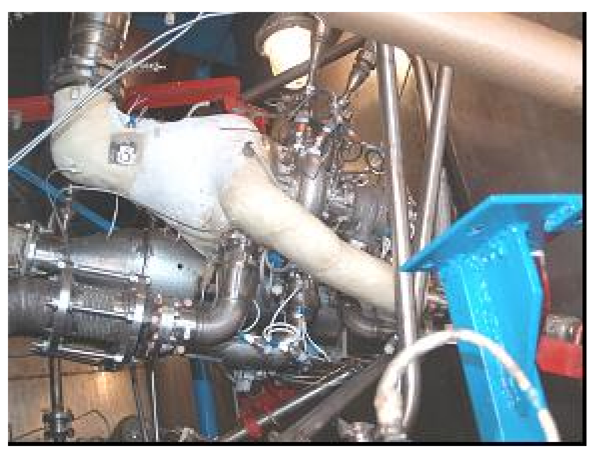


Figure 15. SSTP rig mounted on the test bench

Test program preparation included the development of the chill down requirements and two tests plans– one for a short test and another for a longer test. Facility provided gaseous hydrogen was used to drive the turbine.

The complexity of test program of second test should be noted (Figure 16). Small but significant flow rate changes through the pumps were accomplished during the tests. The flow rate for each pump was changed twice. The SSTP was operated with nominal flow before and after each of the flow rate changes. At the beginning and at the end of the tests the SSTP was operated at partial power. Comparison of the various part power, full power, and mixture ratio test points between run 1 and run confirmed the consistent and repeatable operation of the SSTP as well as it's conformance to specifications

SSTP teardown inspection was performed after the tests. The SSTP disassembly and inspection did not identify any reportable defects. The inspection results were documented and provided to PWR. The SSTP was then re-assembled and delivered to PWR.

These tests confirmed the effectiveness of KBKhAs' incremental development methodology approach. All the results were consistent and the understanding of the turbopump was more complete than if the pump were tested only as an assembly or at engine level. The thorough understanding was achieved in a more timely manner, enabling feedback to improve the design and minimizing the adverse impact of these discoveries during testing.

VIII. Tests planned at PWR

PWR has continuing plans for the SSTP including potential testing as a turbopump assembly in the US. After gaining an understanding of the SSTP component testing in Russia, the SSTP can now be incorporated into an RL10 test engine for engine level testing including evaluation of start and shutdown transients, full power, and partial power operation.

In combination with advanced thrust chamber assemblies currently being developed by PWR and KBKhA, the SSTP can be used to explore a family of enhancements to the existing RL10 engine. Possibilities include a 35,000 lbs thrust engine, increasing the run duration and number of starts at the current thrust levels, reducing tank pressurization requirements, and generating modified cycle expander engines with even greater capability.

Additionally, these components in combination with other development activities expand our knowledge base and facilitate demonstration of other capabilities including alternate propellants, control methodologies, and manufacturing approaches. Through a combination of such technologies it is possible to provide engines that are more robust, may be significantly lower cost, and maintain the safety, reliability, and performance required.

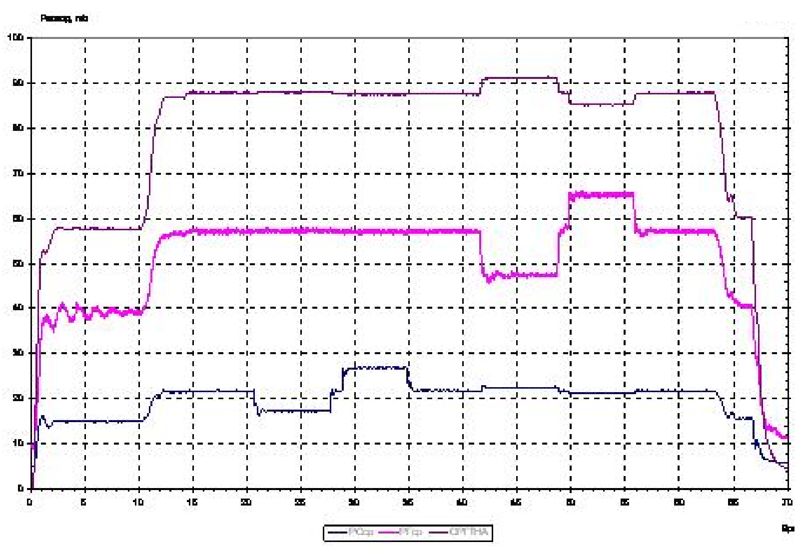


Figure 16. SSTP parameters during 2nd LH2-LOX test

IX. Conclusion

1. The single shaft turbopump created by PWR and KBKhA provides new possibilities for the RL10 engine:

– Enhanced robustness and off-design operability, increased run duration at current thrust levels;

– Increased thrust up to 35,000 pounds;

– Operate with reduced hydrogen inlet pressure that can enable reduced tank pressurization.

2. Testing with simulation fluid ensured the required functional characteristics and performance early in the design phase and made it possible to determine, and adjust if necessary, the margins of performance of these elements before the component delivery and engine level test.

3. One important advantage of sub-component testing simulation fluids (water and air) is to determine operability limits and identify required improvements that should be made before the delivery of finally manufactured components and/or engine testing.

4. The SSTP tests with LH2 and LOX confirmed the results of the sub component tests in simulation fluids and the value of gaining this understanding through inexpensive sub-component rig these rather than during more expensive and risky engine or even assembled component testing.

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