PREFERRED
RELIABILITY
PRACTICES

HIGH PERFORMANCE LIQUID HYDROGEN TURBOPUMPS

Practice:

Understanding and addressing the design environment, component interactions, and potential failure modes are the keys to high reliability in high performance liquid hydrogen turbopumps for launch vehicle engines. Designing and using a combination of unique sealing, cooling, processing, material selection, and balancing techniques in response to engine design requirements will permit the development, production, and reliable flights of hydrogen turbopumps.

Benefit:

Use of precision design; manufacturing; and advanced material selection, fabrication, and treatment techniques will ensure reliable operation of large, high performance liquid hydrogen turbopumps. Many of these practices will also lengthen the operational life of the turbopump, increasing the number of uses before teardown, inspection, refurbishment, and re-assembly for subsequent flights. In addition to higher reliability, lower costs and continued assurance of high performance are resulting benefits.

Programs That Certified Usage:

Space Shuttle Main Engine, Liquid Hydrogen Turbopump, and Alternate Turbopump Program.

Center to Contact for More Information:

Marshall Space Flight Center (MSFC)

Implementation Method:

I. Background:

The 85,000 horsepower liquid hydrogen turbopump being flown on each flight of the Space Shuttle represents almost three decades of design, development, and fine-tuning of its performance and reliability. It is a three-stage centrifugal pump driven by a two-stage hot gas turbine. The pump rotates at 37,000 revolutions per minute (RPM) which is over 600 revolutions each second. The high horsepower, high RPM, high flow rates, and high pressures in this turbopump created a unique set of design and engineering challenges to the prime contractor and to NASA (Marshall Space

MARSHALL SPACE FLIGHT CENTER

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Flight Center). Problems have been encountered over the years that manifested themselves in bearing wear, turbine blade cracking, turbine blade erosion, and rotodynamic issues. In overcoming these problems, specific design features, materials, and fabrication methods have been developed and perfected for the hydrogen turbopump that permit the Space Shuttle Main Engine (SSME) to maintain its unprecedented high performance while exhibiting manned space flight levels of reliability. The practices that have been developed and included in this document are essential to the continued high reliability of the SSME and can also be applied in next-generation turbopumps for reusable and expendable launch vehicles.

II. Bearings and Blades

The two major components of the fuel turbopump that have required focused engineering and manufacturing attention are the turbopump bearings and the turbine blades. Both the bearings and the blades have performed well in initial firings and flights of the engine, but have resulted in unsatisfactory condition reports when subjected to detailed inspection on disassembly after flight. The bearings have exhibited wear before their expected rated lifetime has been reached, and tiny hairline cracks have been observed in the turbine blades.

Fractures in bearing cages were discovered during disassembly inspection of the turbopump in early engines. Investigations indicated that the failures were most likely due to high cycle fatigue; and stress analyses showed a marginal factor of safety on high cycle fatigue for “infinite” life.

Post disassembly inspection of some engines also revealed rub marks, evidence of wear, and indentations on bearing races and balls. Although the slightly damaged bearings were still suitable for development testing, a bearing wear potential prior to end of rated life still exists.

Reliable, long-life fuel turbopump bearings are made possible by sophisticated cooling arrangements and by careful material selection. The fuel pump bearings are cooled by internal flows of liquid hydrogen. The coolant source for pump-end bearings, including an axial load-carrying thrust bearing, is the output of the first impeller of a three-impeller fuel pump. Liquid hydrogen flows from the back face of the impeller through orifices in the impeller hub, through the bearings, and back into the pump inlet. The bearing inner races are clamped to the pump shaft with the bearings free to slide axially within the bearing cartridge. Liquid hydrogen performs the function of a highly effective coolant because all heat is removed from the bearings, resulting in very little, if any, bearing wear. Bearing specifications are very tight, minimizing bearing defects. An alternate bearing material, silicon nitride has successfully demonstrated long life in oxygen turbopumps and the same benefits are expected in hydrogen turbopumps. The provision of ample cross-sectional area and the addition of Fluorinated Ethylene Propylene (FEP) coating to the bearing cages eliminated a bearing cage cracking problem.

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The turbine blades experience enormous centrifugal force loads as well as high thermal loads at 600 revolutions per second. High cycle fatigue and hydrogen embrittlement effects, have caused small hairline cracks in the turbine blades of the high pressure fuel turbopump. These cracks are an order of magnitude shallower than the critical depth of 0.100 inch, but have persisted throughout the program. Although the hairline cracks are not detrimental to performance, periodic disassembly inspection is needed to continue to monitor this condition. Attention is given to blade porosity after machining ($\leq$5 mil pores). Shot peening of blades on the blade-to-wheel interface improves toughness and resistance to cracking. Gold plating of blade shanks resists hydrogen embrittlement. An important design feature in the turbine blade-to-wheel connection is a “loose” fit that gives the blades freedom to adapt to dynamic turbine environments.

III. Turbopump Seals

One of the keys to high reliability liquid hydrogen turbopumps is the use of a variety of compression and flow restricting seals. The compression seals, which include gaskets and piston rings, contain the liquid hydrogen and hot gas inside the pressure vessel or chamber. Flow restricting or flow redirecting seals restrict liquid hydrogen and hot gas flow in one direction and/or redirect flow in another. The principal types of seals are pump interstage (or “damping”) seals, fluorocarbon seals, liftoff seals, labyrinth seals, platform seals, and turbine blade tip seals. The interstage seals permit a small amount of liquid hydrogen to flow between impeller stages. A knurled surface on the seals at the impeller interface slows down axial and circumferential flow of liquid hydrogen and traps enough fluid to provide cooling and vibration damping. Stepped fluorocarbon seals that contact ridges around the impeller face on all three pump stages control the amount of propellant flow around the impeller front shrouds. The liftoff seal assembly, which acts as a check valve ---permitting flow in only one direction---prevents hydrogen leakage into the turbine end of the turbopump prior to engine start and after engine cutoff. During engine start, a pressure unbalance develops across the seal to offset the spring load and retract the seal, allowing liquid hydrogen to enter and cool the turbine end. A turbine hub labyrinth seal directs part of the coolant flow from the liftoff seal to the bearings, disc, and coolant liner to cool the turbine end bearings and discs. Forward and aft platform seals restrict flow and enhance cooling balance while maintaining efficiency of the first and second stage turbine wheels. Turbine blade tip seals help direct hot gas flow through the turbine blades, improving turbine efficiency. One of the most critical seals in the high pressure fuel turbopump is the lift-off seal. Avoidance of contamination is important because it must act as a static seal when closed. It must avoid trapping contamination, and work properly repeatedly in the dynamic engine environment. Repeated and consistent response to pressure differentials is required. The seal must resist rubbing and wear while retaining its capability to pass fluids reliably when open and to seal off fluids completely when closed. The seal is a complex component in itself, incorporating 55 springs, guide bushings, carbon nose, adaptor, retainer plate, and additional secondary seals.

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IV. Materials and Fabrication Methods

Because of the hydrogen environment, the wide temperature ranges, the high structural and thermal stresses, and the close tolerances encountered in the turbopump; a thorough knowledge of material properties is necessary, and precision fabrication methods must be used. A variety of manufacturing techniques are used such as TIG (tungsten inert gas) welding, EDM (electrodischarge machining), conventional machining, investment casting, CNC (computer numerically controlled) machining, broaching, grinding, polishing, and burnishing. Directional solidification is used when casting the turbine blades to produce grains parallel to the major operational stresses. Copper and gold coating and plating techniques are used to protect certain critical components such as turbine housing struts and the blade attachment "firtree" slots in the turbine discs from hydrogen embrittlement. Replacement of sheet metal components with castings eliminates and/or reduces potential hardware failures due to welding defects. Replacement of some titanium rotating components with Inconel 718, the addition of a baked-on dry film lubricant, the use of stellite bore inserts, and the use of knurled pump inserts to smooth out and enhance the damping characteristics of coolants resulted in beneficial improvements in turbopump reliability and lifetime.

V. Advanced Design and Inspection Methods

Advanced computer simulations are now available to characterize the flows, stresses, and thermal environments in rocket engine fuel turbopumps. Computer analyses, well anchored and authenticated by thoroughly instrumented tests, will do much to provide the most reliable and effective turbopump design. Verification of design environments is essential. Advanced computed tomography inspection of critical fuel turbopump components such as the first and second stage turbine blades has been proven to be an effective way to screen the hardware for potential blade failure modes. Sophisticated analytical techniques and precise balancing methods were used in solving a "subsynchronous whirl" problem that caused spurious turbopump vibrations.

Technical Rationale:

Specific design features, materials, and fabrication methods must be used in high performance liquid hydrogen turbopumps to ensure satisfaction of performance requirements while exhibiting manned space flight levels of reliability.

Impact of Nonpractice:

Insufficient sealing of hydrogen liquid or hydrogen gasses in the fuel turbopump could cause improper operation and/or loss of hydrogen to the environment, causing a potential catastrophic fire or explosion. Failure of bearings or turbine blades could cause loss of power and turbopump

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in operation. Failure to operate could result in mission abort, and an explosion could cause loss of life as well as the mission hardware.

Related Practices:

1. Practice PT-TE-1439, "Systems Test Considerations for High Performance Liquid Rocket Engines."

2. Practice PD-ED-1269, "High Performance Liquid Oxygen Turbopumps."

References:

1. Engineering Change Proposal #11-17R1: Space Shuttle Main Engine, Rocketdyne Division of Rockwell, International, Canoga Park, CA, 1988.

2. Space Transportation System Training Data: Report No. ME-110(a) R1R, Rocketdyne Division of Rockwell, International, Canoga Park, CA, December 1991.

3. "Space Shuttle Main Engine Instrumented High Pressure Fuel Turbopump Technology Test Bed Testing Results Summary," AIAA Report No. 93-1908, June 28-30, 1993.

4. "Fabrication of the Space Shuttle Main Engine High Pressure Fuel Turbopump," Marshall Space Flight Center, Huntsville, AL, April 1994.

5. "Solution of the Subsynchronous Whirl Problem in the High Pressure Hydrogen Turbomachinery in the Space Shuttle Main Engine," Paper # 78-1002, AIAA/SAE 14th Joint Propulsion Conference, July 25-27, 1978.