

History of Space Shuttle Main Engine Turbopump Bearing Testing at the Marshall Space Flight Center

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Introduction

The Space Shuttle is propelled into orbit by two solid rocket motors and three liquid fed main engines. After the solid motors fall away, the shuttle engines continue to run for a total time of 8 minutes. These engines are fed propellants by low and high pressure turbopumps. A critical part of the turbopump is the main shaft that supports the drive turbine and the pump inducer and impeller. Rolling element bearings hold the shaft in place during rotation. If the bearings were to fail, the shaft would move, allowing components to rub in a liquid oxygen or hydrogen environment, which could have catastrophic results. These bearings are required to spin at very high speeds, support radial and axial loads, and have high wear resistance without the benefit of a conventional means of lubrication.

The Rocketdyne built Shuttle turbopumps demonstrated their capability to perform during launches; however, the seven hour life requirement was not being met. One of the limiting factors was the bearings. In the late 1970's, an engineering team was formed at the Marshall Space Flight Center (MSFC), to develop a test rig and plan for testing the Shuttle's main engine high pressure oxygen turbopump (HPOTP) bearings. The goals of the program were to better understand the operation of bearings in a cryogenic environment and to further develop and refine existing computer models used to predict the operational limits of these bearings. In 1982, testing began in a rig named the Bearing and Seal Material Tester or BSMT as it was commonly called. The first testing investigated the thermal margin and thermal runaway limits of the HPOTP bearings. The test rig was later used to explore potential bearing improvements in the area of increased race curvatures, new cage materials for better lubrication, new wear resistant rolling element materials, and other ideas to improve wear life. The most notable improvements during this tester's time was the incorporation of silicon nitride balls and bronze filled polytetrafluoroethylene (PTFE) cage inserts into the bearings and the anchoring of the SHABERTH bearing model and SINDA thermal computer model for cryogenic bearing analysis.

In the mid 1990's, Pratt and Whitney (P&W) won the contract to deliver new high pressure turbopumps for the Shuttle's engines. P&W used two new bearing materials for the rings, Cronidur 30 and AISI 9310 steel and testing was needed on these new materials. A test rig had been designed and delivered to MSFC for testing hydrostatic bearings but with the need by Pratt to validate their bearings, the rig was reconfigured for testing of two ball bearings or a ball bearing and a roller bearing. The P&W bearings are larger than the Rocketdyne bearings and could not be installed in the BSMT. This new test rig was called the LH2 test rig and began operation in 1995. The LH2 test rig accumulated 75,000 seconds of run time in hydrogen. This test rig was valuable in two areas: validating the use of silicon nitride balls and rollers in Alternate Turbopump Development (ATD) bearings, which Pratt eventually used, and in proving the robustness of the balls and rollers after "river marks" appeared on the surface of the rolling elements.

Individual test reports have been presented at conferences and symposiums throughout the years. This paper is a comprehensive report of all the bearing testing done at Marshall. It represents thousands of hours of dedication and labor in all engineering and technical fields that made this program a success.

Bearing and Seal Material Test Program

The Shuttle's high pressure oxygen turbopump was not meeting its life goal of 7.5 hours before refurbishment. The lack of performance and life of the main shaft bearings was one of the prime factors.

One failure scenario postulated was that the bearings were getting hot during operation and did not have enough coolant flow or sub-cooling to remove the heat, resulting in high internal temperatures. The bearing thermal characteristics needed to be known along with how much thermal margin existed in the turbopumps. Another concern was how close to a thermal runaway situation existed and what would happen if the bearing did suddenly increase in temperature. Management at MSFC approved funding for the test program to go investigate the concerns of the bearing community. SRS Technologies (now NeXolve) was brought in as a consultant to follow testing and analyze data, and by using the SHABERTH bearing code and SINDA thermal code, develop a cryogenic bearing analysis code that would be useful in predicting bearing performance.

The test rig was designed to duplicate the HPOTP operating conditions and be instrumented with pressure, temperature, accelerometers, displacement, and speed sensors for data analysis. There were devices to add external axial and radial loads to the bearings as well. The BSMT runs at 30,000 rpm for a predetermined amount of time or to run tank depletion. The power to spin is provided by a 450 hp diesel engine through a speed increaser. Four bearings were installed on a horizontal shaft as pairs in a back to back orientation. The bearings have an axial preload via springs and the operational Hertzian stress level is in the range of 2GPa (300KSI). Liquid oxygen flows through each bearing pair and out of the test rig. The quality of liquid is controlled by allowing the run tank to heat up the fluid. The test articles were Rocketdyne high pressure oxygen turbopump (HPOTP) bearings, 57 mm (2.25 inch) bore, 440C CRES steel, angular contact design. The DN value is 1.7 million. The ball separator (aka cage) is made of PTFE coated glass fabric wound into a cylinder and machined into a cage. The glass fibers in the cage are thought to induce heat into the bearings through friction against the rolling elements. All the active surfaces of the bearing races and cage received a coating of molydisulfide. This coating was useful for startup but quickly wore away during rotation.

The first BSMT built was installed in 1982. Checkout runs for the facility, data collection, and operating procedures were completed and testing began. During one of the early runs in LOX, an incident occurred and the test rig caught fire, damaging the test rig and the facility. An investigation determined that one end of the tester lost coolant flow thru the bearings and overheated, causing the fire. Piping changes were made in the LOX supply system; however, a decision was made to run liquid nitrogen (LN2) in future tests for safety.

The BSMT was rebuilt and the test stand repaired. One of the early investigations was to determine how flow rate affected the heat generation in the bearings. This test run would also serve to validate and improve the computer analysis model SRS was developing. Two LN2 flow rates of 4.6 lbs per second and 9.2 were chosen for test purposes. After an hour of total run time at 4.6 lb/sec, one of the bearings showed spalling and distress. Evidence of wear and ball skidding was visible in borescope inspections. Temperature spikes were seen on the outer race thermocouple to correlate with ball skid also. The flow rate was increased and tests continued. The temperature spikes decreased and 900 more seconds were run on this build. Severe wear and ball skidding was seen and the rig was removed from the stand. This test showed that increased coolant flow increased the heat generation margin in the bearings and allowed the tester to run after the onset of surface distress.

The next test series was used to investigate thermal margins of the bearings. It was believed that thermal instability could be created in the tester by reducing the coolant flow rate thru the bearings or lowering the sub-cooling margin of the fluid. This test series and all others afterwards were run in liquid oxygen. Measurement of the outer race temperature would give SRS data to put into their models to predict bearing operating temperatures and help to establish thermal margins in the turbopump. Two thermal excursions occurred in this build of the rig. One bearing experienced high outer race temperatures at 17 degree sub-cooling (below the saturation line) and another bearing in another test run at 21 degree sub-cooling. These temperatures correlated closely to the SHABERTH/SINDA model predicted sub-cooled temperatures of 13 to 15 degrees below the saturation line. It was relevant that these two bearings continued to operate for four more tests without thermal instability. Redline cuts on the outer races shut the tester off during the thermal runaways and limited the maximum temperature reached. Data plots of outer race temperatures also verified that an event had occurred. After the ninth rotation, borescope inspection showed that the two inner bearings were severely discolored and worn to

the point of losing axial preload and the balls were no longer rolling but were sliding in their races. A decision was made to pull the rig and inspect the hardware.

Bearing inspections were performed and it was noted that the visual degradation characteristics were essentially identical to those seen in the SSME developmental engine bearings. The outer race showed negative contact angle with discoloration, the inner race had a very heavy load path low in the curvature with discoloration and a jagged upper shoulder edge. The balls were worn and black in color with skid marks on the surface, and the cages from the inboard bearings were heavily worn and damaged. Some of the cage webbings were worn thru and ball pockets were egg shaped. Metallurgical analysis showed that the balls had a micro surface layer hardness of three points higher than the substrate indicating high temperatures and quenching when the tester shut down.

This test series was very important to the bearing community. It showed that bearing degradation in the tester was similar to degradation in the turbopumps. By lowering the sub-cooling margin of the propellant, a thermal instability occurred very rapidly without warning from the instrumentation. After the excursion, the bearings operated at an increased temperature but without another high temperature event. Severe wear occurred in the bearings during the thermal event due to a loss in internal clearance increasing contact stresses, causing wear of the balls, allowing the contact angle to increase to the point of the balls going to the top of the inner race shoulder. The data from the test also linked the computer model predictions to actual events and gave confidence that the model could be used for future HPOTP bearing design analysis.

Knowing that the bearings have no lubrication except from a minute transfer film of the Polytetrafluoroethylene (PTFE) from the cages to the balls, several attempts at improving the lubrication and lowering the heat generation in the bearings was investigated. One idea was to vacuum impregnate the cages with LOX compatible oil. The intent was to have a thin film of oil on the cages that would not freeze up the bearings during chill down and during rotation, the oil would reach its melting point and provide a thin film of lubrication to the balls and rings. Testing of this concept showed that it was not a feasible option to pursue. Surface distress occurred on the balls earlier than a standard HPOTP bearing and the test was stopped. Thoughts were that the frozen oil degraded the surface of the balls causing wear or the frozen oil inhibited the transfer of PTFE film or a combination of both shortened the life of the bearings. Another method was to apply LOX compatible grease with a heavy percentage of molydisulfide into the cage pockets. This concept was tried with no success. Controlling the amount of grease applied was difficult and the grease was dispersed during balancing operations. A third concept investigated was pre depositing a thin film of bronze filled PTFE on the races of the bearings. A piece of PTFE was placed in a holder and by using a spring loading mechanism, the PTFE was loaded against the races while they were rotated for a period of time. Even though the application process was variable, the bearings ran for 51 minutes in the BSMT.

In an effort to reduce heat generation, one build of the BSMT had bearings that were reground in the inner ring to a more open curvature. The machine shop at MSFC reground four Phase 2 inner rings for this test. The idea was that less rolling contact and ball slippage would reduce the thermal load. When the curvature is opened up, the Hertzian contact stresses go up. No improvement was seen in this build of the BSMT.

Thin dense chrome (TDC) was receiving attention as a wear resistance coating on bearings during some of the testing years. In an effort to decrease wear of the rings, four bearings were sent out to go thru the process of applying thin dense chrome and being installed in the test rig. The bearings were received and installed, but during balancing operations in which the bearings spin at 1000 rpm for a short amount of time, the balance assembly generated a large amount of heat and locked up. The consensus was that the TDC changed the internal geometry of the bearing and there was no diametrical clearance available and the contact angle changed to such a degree that made the bearings unusable. These bearings were never tested.

Another concept that was never installed in the BSMT was carbon fiber cages. Cages were made from carbon fiber and received at MSFC. Upon inspection, the cages were found to have voids in the wrapped

layers and were fragile. The cages had to be handled very carefully and were considered not structurally sound for testing.

New materials and processes were also tested in the BSMT. CRB-7 steel and MRC 2001 powder metal processed material were made into HPOTP bearings and installed for tests. CRB-7 showed no improvement over the 10 to 15 minute benchmarked life time. MRC 2001 did increase the life of the bearings approximately 10X over the benchmark. This material was new and the manufacturing process not well understood, however, this was a significant improvement over 440C steel. It may have received more attention if not for silicon nitride material rolling elements and the results that were obtained during testing of this material.

Silicon nitride is a hot isostatic pressed material that received attention for bearing elements back in the 1970's with little success. Through the years, the manufacturing process and material was improved to a degree that made it a candidate for testing. Rolling contact testing at MSFC had also shown excellent results in fatigue life at elevated stresses. Silicon Nitride balls were procured from a domestic vendor for replacement of the 440C steel balls. Computer modeling by SRS Technologies showed that using silicon nitride balls would increase the Hertzian contact stress to 2.6 GPa (377KSI) and decrease the predicted life of the bearings. The HPOTP bearings were not reaching their predicted fatigue life now so this was not an issue. The first hybrid cryogenic bearings were installed and tested in the BSMT in August of 1990. Because this was the first test of this material and experience needed to be gained, the test plan was conservative. Test times at 30,000 rpm were 2, 5, 10, and 2 minutes. The 10 minute run was continuous, which was almost the benchmark set for total time of the 440C bearings in LOX. A total of 27 rotational minutes was achieved which was a milestone for this test rig. During borescopic inspections, it was noted that three balls had spalled similar to steel balls. As more test were run, the spalls increased in size, but no catastrophic failure occurred. The last 30,000 rpm run was cut due to excessive temperature on the outer race of a bearing and a decision to disassemble the rig and inspect was made.

The bearings were taken to the Materials and Processes Metrology Lab for inspections. The outer races had slight roughness in the wear tracks but no negative contact angle indications; the inner races had moderately rough wear tracks in the active zone with no high shoulder contact, the cages had only light rubbing contact marks, slightly heavier on the coolant inlet side. Diameter measurements of the balls showed very little wear or change in size from ball to ball and bearing to bearing. Data showed that the bearings ran without a large increase in temperature also. Conclusions made were that the silicon nitride/ 440C hybrid bearing had potential in lowering heat generation, increasing thermal margin, increasing wear resistance, and improving the overall performance of turbopump bearings running in cryogenic fluids.

Based on the success of the first test, a second build of domestic, silicon nitride hybrid bearings was completed. This unit had a Hertzian contact stress of 2.5 GPa (362 KSI) due to a lower axial load. This unit accumulated 111 minutes at 30,000 rpm. It was noted that parallel striations on the balls were seen early in testing and small pits after 49 minutes. At 67 minutes, spalling was documented on 1 ball in one bearing. Another 44 minutes was run after the spalling was noted. Inspection of the bearings showed more surface distress in the active zones on the steel races but no reverse angle outer race track or high shoulder contact. The cages showed slightly heavier contact due to extended run times. Examination of the balls showed very little diameter wear and high precision traces showed very little out of round conditions. The heavier loaded bearings had the most surface distress in the races and one bearing had four balls with minor spalling or pitting and one ball with a large spall.

The Tribology Team also evaluated silicon nitride ball material from Japan. This material differed from the domestic material in the use of the sintering agents used in the manufacturing process. The balls were installed into Phase 2 SSME bearings, the rig assembled, and delivered to the stand, and testing began. After seeing the results from the earlier silicon nitride tests and learning how this material responds in highly loaded cryogenic bearing applications, expectations were high. The test results on this material were excellent. Twenty four rotational tests were run for an accumulated time of slightly over 7 hours. Fourteen of the rotations had an extended run time of over 20 minutes; tests were cut due to LOX run tank depletion. After six hours of time, a surface anomaly was seen on three balls in a heavily loaded

bearing that was described as a "river mark". This was based on the observance that the indication had more width than depth and ran along the surface of the balls and resembled the way a river would look on a map. This was determined to not be a crack in the material. The bottom of the mark was flat and the thought was that this would not penetrate deeper into the ball material. Three more full duration tests were run after this with it documented that the river mark grew in length and started to branch out with smaller indications from the main anomaly. The test data indicated that there were no thermal excursions in any of the bearings during rotation. The test rig was pulled and bearing inspections began.

Ball inspections showed very little diametric wear from ball to ball. This was an important finding in that ball to ball diameter variations can affect cage loading and Hertzian contact stresses internal to the bearing. Cage pocket contact with the balls was also light. No deep wear pockets or scars were visible in the cage pockets. With the extended run times, the inner races of two bearings showed spalling but did not degrade the balls.

From all the years of testing and products evaluated, silicon nitride hybrid ball bearings showed the greatest improvement. Even with the river mark surface anomaly, the hybrid bearings showed that they were a viable candidate for use in SSME bearings. The river marking has not been fully understood to even now. Thoughts range from traction marks from the high Hertzian contact stresses combined with the cold cryogenic temperatures, differences in sintering agents from domestic to foreign suppliers, flow of coolant across the rotor creating a static electricity build up, or Lichtenburg effects due to the discharge of static electricity over the surface of the balls. It is known that silicon nitride material isolates the rotor from ground and that electrical arcing will occur across small gaps such as a laby seals to sealing rings, creating small pits. Methods are used today to ground the rotor in turbopumps using hybrid bearings.

In an effort to reduce internal heat generation in the SSME bearings, new cage materials were being evaluated. Battelle Labs was looking into low friction, low heat generating materials to replace the PTFE coated fiberglass cloth being used. Laboratory testing had shown that two materials might work; bronze powder filled PTFE and bronze powder with 5% molydisulfide (MoS₂) PTFE. Both materials showed a low coefficient of friction and were LOX compatible. The negative side was that both required a rigid structure as the materials did not themselves have the structural strength to be made into a cage. A design was developed and fabricated and delivered to MSFC. Two test series with bronze powder and PTFE were run with excellent results. The first test series accumulated 70.5 minutes and the second 69.5 minutes with LOX tank depletion runs on both test builds. Borescope inspection between tests showed that bronze transfer film was visible on the balls after the first spin test. The testing was stopped after the inner bearings experienced wear and temperature increases on the outer races cut the tests. Bearing inspections showed heavy wear on the most heavily loaded bearings but evidence of a bronze transfer lubricating film. The cage inserts withstood the ball to cage forces without deforming or showing signs of heavy wear.

The cages with 5% MoS₂ combined with the bronze powder/PTFE material were tested next. . The test only accumulated 22 minutes over 7 attempts with no LOX tank depletion runs. The borescope inspection after seven minutes showed dark balls and minor spalls on one heavily loaded bearing. After 22 minutes, balls were worn to the point of loss of bearing preload and heavy upper shoulder contact on the inner ring. The BSMT was pulled for bearing inspections. Ten of the twelve cage inserts were found to be cracked with small pieces of the inserts missing. Scanning Electron Microscopy showed that the inserts had experienced a brittle type failure. Visual examination revealed heavy rubbing in the cage pockets and severe wear and spalling of the bearing rings. The test results were not encouraging enough to carry on testing with this material.

In the early 1990's, MSFC was able to test a Shuttle main engine in the Technology Test Bed (TTB) program at Huntsville. This would be an opportunity to implement bearing improvements from the test program into actual hardware and see how it performed at hot fire conditions. The program office wanted more testing of the new cage materials and silicon nitride hybrid bearings before allowing them to be installed into a turbopump. An additional requirement of applying a radial load on the test bearings was imposed to replicate the running conditions in the pump. Two builds of the rig were tested to meet the program's requirement. The first qualifier build used domestic silicon nitride balls, a higher axial load, and

a 680 pound radial load. The calculated Hertzian stress was 3.4 GPa (493 ksi). As a confidence builder, the bearings were also subjected to an axial quick hit load of 6000 pounds on the last test. This rig ran for 126 minutes at 30000 rpm with no issues. The second assembly used foreign made balls plus had the bronze PTFE cages installed. This build ran for 106 minutes at 30000 rpm with no issues. Overall, the BSMT ran approximately 14 hours of time on silicon nitride ball bearings representing 20 bearing samples. From this testing, a bearing with silicon nitride balls and steel rings with a standard cage (not the bronze/PTFE design) was installed into the pump end of a Rocketdyne turbopump and tested on the TTB stand. The turbopump ran for 800 seconds with no known bearing issues. This turbopump was returned to Rocketdyne and the bearing was not returned to MSFC.

The BSMT program was a huge success for MSFC and the bearing community. Many hours of test rig activities and data analysis was completed providing a lot of useful information on cryogenic bearing behavior. New bearing materials were evaluated and computer analysis models were implemented, proven, and used for analysis of test rigs and turbopumps. Pratt and Whitney began to build high pressure turbopumps for the Shuttle in the 1990's and their bearing design was different from Rocketdyne's. The BSMT test rig was retired in 1994.

P&W LH2 Test Program

The Tribology Team at MSFC had become interested in testing hydrostatic bearings for future program high speed turbopumps. A rig for this testing was designed by P&W, fabricated, and delivered to Marshall in 1995. In its current design, the rig would be assembled with three hydrostatic bearings and had instrumentation for measuring pressures, temperatures, movement, and speed in the test rig. It was designed for liquid oxygen or hydrogen use and could be used to determine rotordynamic coefficients of fluid film bearings. In this same time span, P&W had become the supplier of high pressure pumps and needed to validate ball and roller bearings as part of the SSME plan. P&W was also seeing river marks on the silicon nitride balls and rollers in turbopumps and the consequences of these indications needed to be evaluated. The BSMT was not capable of supporting this task so the hydrostatic bearing test rig was redesigned for rolling element bearing testing. The test rig was modified to run either ball/ball or ball/roller bearings and still included a hydrostatic bearing in one position. This rig was named the LH2 Test Rig and testing began in 1996. The test plan was to accrue 60 mission cycles equivalent to about 32000 seconds with an intermediate tear down and inspection at the half way point.

This test rig design was a major change from the BSMT. This rig had a vertical shaft layout, two rolling element bearings above one hydrostatic bearing, driven by a gaseous nitrogen Terry turbine. The center bearing was in the test position and a means of applying a radial load on this bearing was incorporated. Internal pressures, bearing loads, speed, and flow rates were similar to the P&W's high pressure fuel turbopump. A thrust chamber was incorporated into the bottom of the shaft to apply axial loads to the bearings and support the shaft when testing a roller bearing. Flow rates of hydrogen thru the bearings were in the 0.5 lb per second range. The tester rotational speed was 35000 rpm and test would go to run tank depletion if not cut by a redline parameter. P&W used several materials in their bearing design. Cronidur 30 for rings had become available and had better stress corrosion cracking properties than 440C. They had a cage design using fiberglass cloth supporting bronze/PTFE inserts and were using silicon nitride balls and rollers in their pumps. P&W had found river marks on their silicon nitride bearing rollers and balls similar to the ones developed at MSFC in the BSMT. A need existed to determine the robustness of silicon nitride and investigate the long term running durability of silicon nitride with river marks. SRS Technologies (now NeXolve) was on board during testing to help set up test parameters, review data, and build a computer model for this rig. Another bearing computer analysis program became available during this time also. Advanced Dynamics of Rolling Element Bearings, ADORE, by Pradeep Gupta, was delivered to MSFC and installed on a CRAY computer. This program predicts cage to ball loads in a dynamic mode. This program has since been upgraded and can run on a desktop computer.

The first assembly of the LH2 test rig was used to validate the assembly of the tester, verify control procedures, instrumentation and data collection, and demonstrate safe operation at the test stand. The rig was assembled with a steel ball bearing in the reaction position and a silicon nitride ball bearing in the test position. A short checkout series had issues with axial loading differential pressure control and speed measurement. This tester was originally designed for hydrostatic bearings and as such, the axial loading method for rolling element bearings had not been tested. The turbine drive pressure would couple with the thrust chamber pressure and upset the balance ratio between the top of the tester and the bottom. The speed sensor was a proximity probe and dropped out when the shaft moved an excessive amount. A method to control shaft axial position in the rig was developed and written into the control software. It was determined that the Terry turbine speed was not stable at low speeds (7500-15000), but was more predictable at the higher rotational speeds (30000-40000). An accumulated time of 35 minutes was accrued with 17 minutes at the target speed of 35,000 rpm. Bearing inspections showed that the top bearing (or reaction bearing) was in good condition having signs of bronze transfer film on the balls and races. There was some light debris denting seen in the inner race. The test bearing with silicon nitride balls showed a checkerboard pattern of marks over the ball surfaces. The inner race had mild surface distress in the wear track. Cage pocket contact was light. A decision to install a roller bearing in the test position was made and the tester was rebuilt.

Build one of the LH2 rig included a silicon nitride ball bearing in the top position and a silicon nitride roller bearing in the test position. This roller bearing had slight river marking when installed from previous testing at P&W. It was known going into test that the position of the shaft would have to be held by the pressure differential between the top of the tester and the thrust chamber. The bearing preload spring was instrumented with strain gages and an axial displacement probe monitored the position of the shaft. Three rotations were attempted. Data showed shaft speed was erratic and not constant. Strain gage data indicated the shaft moved axially up and down and rubbed against the thrust chamber. On the third attempt, no rotation was indicated even with 30% higher turbine inlet pressure. Data from the turbine pressure inlet showed that the test rig may have over sped up to 40000 rpm. A decision to pull the rig was made. Inspection showed no harm to the bearings but the thrust chamber and shaft were damaged. It was decided to go back to ball bearings in both locations in the next build. Some modifications to the test procedure were made and a control circuit was added to better control the pressure fluctuations affecting shaft movement.

The second test build utilized ball bearings from P&W, previously run in fuel pumps. The reaction bearing had minor river marks when installed and the test bearing was in excellent visual condition. The leak check on this build resulted in an over pressurization of the rig, thrust loading the bearings heavily. Analysis showed that this bearing may have seen 685 ksi contact stress which exceeded the allowable by 85,000 ksi. Brinelling was suspected and noted. Redlines and control procedures were added to prevent this over pressurization from occurring again. As testing began, speed issues came up again. Speeds of 45,000 were estimated on one test and 60,000 on another test with no indication in the speed sensor. Shaft axial location control was not improved as data showed pressure oscillations and movement. It was decided to stop rotations and perform a non rotational pressure calibration to gain an understanding of the cavity pressures and shaft movement interaction. After data was examined, an automatic routine was put in the control of the tester for shaft movement control. The speed sensor system was also replaced. Four good tests were completed after this change. The tester was removed from the stand after 2500 seconds of run time with 1800 seconds at or above 35,000. Bearing inspection showed that the top reaction bearing had not gained any river marks or existing ones become worse with run time. Brinell marks were not visible, however they did show up on the inner race using Talyrond traces. They were very minor in depth, being 0.1 mil deep. The test bearing had 932 seconds from pump testing before being installed in the rig and was noted as being in pristine condition. Post test inspections showed no change in visual appearance. Brinelling at 0.1 mil deep was seen using the Talyrond machine. The results of the bearing inspections showed no evidence that the tester produces any anomalous wear modes not experienced in engine testing.

The third test build had the goal of demonstrating the durability of silicon nitride elements with river marks. A bearing from engine testing was installed in the top position of the tester. This bearing had the heaviest markings on the balls of any seen before at P&W. The test bearing was the load bearing from

Build 2. In addition to axial preload, it was decided to apply thrust cycles on the bearings during rotation to simulate transient loads experienced in the turbopump. Pre and post test mapping of the balls were done to document the characteristics of the markings. This test rig ran successfully for 520 minutes total time with 440 minutes at 35000 rpm and was cycled 120 times at 5000 pound thrust loads. Bearing inspection showed that the area of the river marks did not seem to grow but smaller "tributaries" branched out from the main marks and covered the surface of the rolling elements. Some debris denting was seen in the races and cage pocket contact was of a moderate level.

The fourth build of the rig was used to compare surface degradation of the domestic and foreign supplied silicon nitride ball materials. New rolling elements were installed in the bearings. The domestic hybrid bearing material was installed in the top position and the foreign hybrid bearing material in the load position. It was known that the load position reacts more of the radial load and transient load and is in a slightly more severe application than the top bearing. Testing was run for 7.5 hours at 35000 rpm. This represents 32 test cycles, most of the testing for run tank depletion around 1000 seconds per test. Transient cycles of 6100 pounds were applied 126 times. At disassembly, river marks were seen on both vendors rolling elements. The domestic made balls had slightly less severe indications than the foreign manufactured ones, but both had river marking to various degrees. This test series along with Build 3 demonstrated the ability of hybrid silicon nitride ball bearings to meet the 60 mission design life even with the formation of river marks on the balls. It also validated the rig as being able to produce the marks under test conditions similar to the environment found in the turbopumps.

It had been observed that river marks seen in the P&W LOX pump were less severe than the marks visible on balls and rollers from the hydrogen pump after hot fire tests. SRS Technologies used the ADORE bearing analysis program to run a comparison of the traction forces and slip velocities in the bearings of the two pumps. Their modeling and analysis showed that the LOX pump has higher local traction forces than the fuel pump. A general statement was made that traction forces may not be responsible for river marks with the caveat that there was some uncertainty in the simulation and more studies needed to be run.

With the success of the ball bearing testing and P&W's desire to investigate the river marks on cylindrical rollers, it was decided to build a ball and roller bearing rig again. Significant changes had taken place in automatic pressure controls, operator experience and procedural improvements, speed sensor operation, and eighteen hours of run time experience had been gained with ball bearings. The roller bearing from Build 2 was installed in the test position and a ball bearing from a hot fired pump was in the top position. SRS ran computer analysis to determine maximum limits for radial loads on the bearings as this load was going to be higher on the ball bearings. Two goals were set for this build. One was to generate life data on the highly loaded ball bearing and the second was demonstrating 60 mission cycle life on the roller bearing. Once again speed and axial shaft position problems occurred. A procedure to apply radial load incrementally as speed increased was developed and when tested, the speed and shaft movement issues became less of a problem. After a successful rotational test, it was decided to apply the full radial load of 1100 pounds at 15000 rpm and increase the speed up the target of 35000 rpm. This gave the best results for steady speed with little shaft movement. However, throughout testing, problems were still experienced with speed control and shaft movements. It was thought that the rollers were skewing in the cage pockets, causing speed issues. The test rig completed eleven tests, some thru run tank depletion (~1000seconds), up to an accumulated time of 3 hours. The tester was still having problems rotating even with higher turbine pressures and at this point, a decision was made to pull the rig and inspect the bearings.

The test rig was taken to the Tribology Lab for disassembly. It was observed that the shaft was difficult to remove from the tester that may have been from galling between the shaft and thrust chamber. No roller skewing was observed. The rolling elements had been inspected pre test so a direct comparison could be made after tests of notable areas. The rollers had experienced less degradation than the balls in the test runs. The ball bearing was subjected to higher radial loads in this build and was expected to have more surface distress. The ends of the rollers showed some burnishing and rubbing from the cage and the cage pockets reflected this rubbing also. The main river marks on the balls did not seem to grow but smaller and narrower marks coming from them were visible. The observation would be similar to

crazing in glass or the Lichtenburg effect seen in plastics. The rollers showed less degradation on the surface. Parallel indications were seen on the roller outside diameters thought to be rubbing of the cage fibers against the rollers. The indications mapped did not grow in severity and the crazing observation was not seen on the rollers.

The LH2 tester had accumulated approximately 21 hours of rotational time on Pratt's bearings including a 3 hour run on silicon nitride rollers. Some of the bearings had been exposed to 60 mission life times, hit with 120 high axial load cycles, experienced 2X rotational speeds and wide speed fluctuations, hit with a thrust overload causing brinelling of the races, and still there were no failures of the hybrid bearings.

Because of test facility schedules and the large amount of time successfully accumulated on the hybrid bearings, the LH2 rig was not rebuilt for further testing. Bearing testing ended in February 1999.

Bearing Analysis and Computer Modeling

The general bearing computer modeling program SHABERTH and the thermal analysis program SINDA was used for early bearing testing. A model of the BSMT test rig was built by SRS using the inputs to SHABERTH to analyze bearing behavior. The SINDA code was used to predict thermal behavior in the bearings. As test data was collected, the models were fine tuned. The correlation between the test rig and computer analysis program became a useful tool during the years of testing to set redlines, analyze bearing behavior, and investigate anomalies that occurred. Bearing analysis codes were also built of the SSME turbopumps to predict behavior and for anomaly investigations. The codes were modified and improved during bearing testing and turbopump hot firing time and are now very reliable in their predictions. The SHABERTH code has been written for personal computer use and now has a simple graphical user interface input screen. This program was developed by SRS and is named the Bearing Analysis Tool or BAT.

The ADORE bearing code was also brought on line during testing. This program has the capability of analyzing bearing characteristics in a dynamic environment. This is useful in determining ball and cage contact forces and traction and slip behavior in bearings. The first version of this program was run on a CRAY computer, but the latest program can be run on a personal computer. ADORE was used during the LH2 test program to determine ball to cage forces and investigate the river marks seen on rolling elements during testing of hot fired turbopumps. ADORE has also been used to model bearing forces and traction in the SSME low pressure and high pressure pumps.

Bearing Test Documentation and Archival

Bearing testing began before personal computers and all the software for report writing and photo documentation were available. Early inspections were done using a 10-50X microscope and hand sketching what was seen on the bearings. A crude device was built to try to determine where the contact path was located in bearing races. Hand held micrometers were used to measure large scale ball wear. VHS tapes were made of the borescope inspections between tests. Polaroid instant film cameras were used for photo documentation. The early test reports were prepared on typewriters and presentations were done using an overhead projector and transparencies. Through the years, significant improvements were made with inspection tools in the lab. High definition video cameras with photo capability at high magnifications are now the norm for bearing inspections. Stereo microscopes with 3D capability are available. The Tribology Lab has high precision metrology equipment manufactured by Taylor Hobson for measuring roundness, surfaces finish, wear, curvature, depth and width of anomalies, flatness, and anything associated with surface metrology. Bearing axial and radial internal clearances and ball diameters can be measured to high precision. The inspections are recorded on disc or in stored in files that with a click, can be sent to anyone needing the data. Test data that was once recorded on multiple 10 inch AMPEX tapes is now recorded on CD's and immediately available for analysis. The vacuum

tube, hand operated facility controllers have been replaced by a personal computers where one person with a mouse click, can start an automated sequence of operations and run an entire test.

Concluding Remarks

Seventeen years of bearing testing have been completed at MSFC. A vast amount of knowledge has been gained in the behavior of bearings running in turbopump environments. New bearing material steels were tested and evaluated and a new cage design was developed during this time. Silicon nitride proved to be an excellent wear resistant material that can be used for rolling elements in high speed bearings. The computer codes of SHABERTH and SINDA proved to be very useful in analysis and accurately predicting operational characteristics of bearings in test rigs and turbopumps. ADORE (Advanced Dynamics of Rolling Element bearings) was developed for dynamic analysis and became applicable for installation on a personal computer. Bearing inspections started as sketches on paper and photos were taken on a Polaroid camera. Inspections are now done on high precision metrology instruments measuring bearing wear to the micro inch. High definition video cameras are now in use. Many people contributed to the success of this program throughout the many years of testing. It is through these efforts that NASA is flying the best bearings in the turbopumps that ensure the safety and success of the missions now and into the future.

Acknowledgments

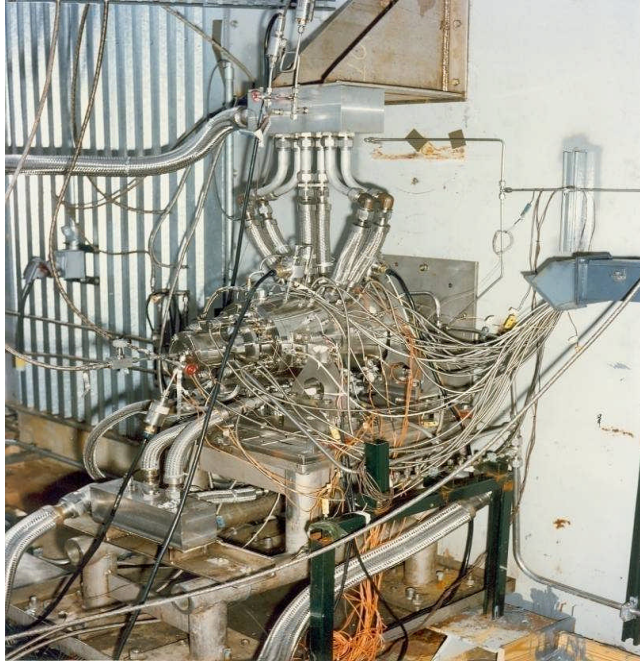
The authors express their appreciation and thanks to all the individuals that worked on the bearing test program in any way for their time, energy, and contributions. To name them all would surely leave someone out. Thanks to the SSME project office for funding this program that delivered meaningful results back to the aerospace community. Special recognition goes to Fred Dolan, MSFC retired, and Joe Cody, SRS retired, Jim Moore, NeXolve, and Dave Marty, NeXolve, for their dedication and time devoted to the start up and success of this program.

The use of contractor names in this report is not an endorsement that their services are better than those that could be procured from another contractor providing similar services. It is to give credit for their contributions in the bearing test program.

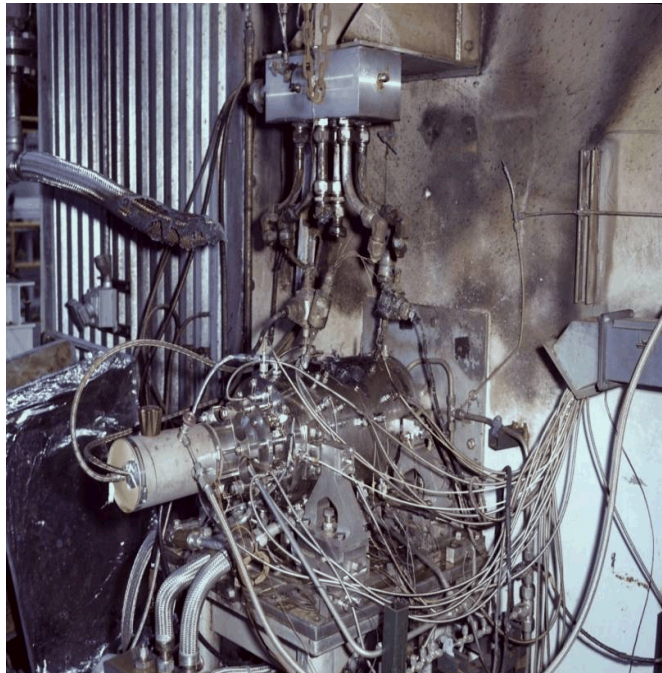
References

- Cryogenic, High Speed, Turbopump Bearing Cooling Requirements, Fred Dolan, Howard Gibson, James Cannon, MSFC, Joe Cody, SRS Technologies, Advanced Earth to Orbit Propulsion Technology Conference, May 13, 1986
- Bearing Test Performed in Liquid Oxygen, H. Gibson and S. Fears, MSFC, Presented at Earth to Orbit conference
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- Overview of Bearing Testing at MSFC, Past, Present, and Future, H. Gibson, R. Thom, F. Dolan, MSFC, presented at AIAA conference
- Liquid Hydrogen Testing of Silicon Nitride Bearing for use in High Speed Turbomachinery, Chip Moore, H. Gibson, R. Thom, MSFC, 32nd Aerospace Mechanisms Symposium, 1998
- Marshall Space Flight Center High Speed Turbopump Bearing Test Rig, H. Gibson, C. Moore, R. Thom, MSFC, 34th Aerospace Mechanisms Symposium, Goddard Space Flight Center, 2000
- SRS Technologies Yearly Contract Reports, 1996, 1997, 1998, Jim Moore, Dave Marty, SRS Technologies, now NeXolve

FIGURES WITH DESCRIPTIONS



BSMT BEARING TEST RIG ON STAND



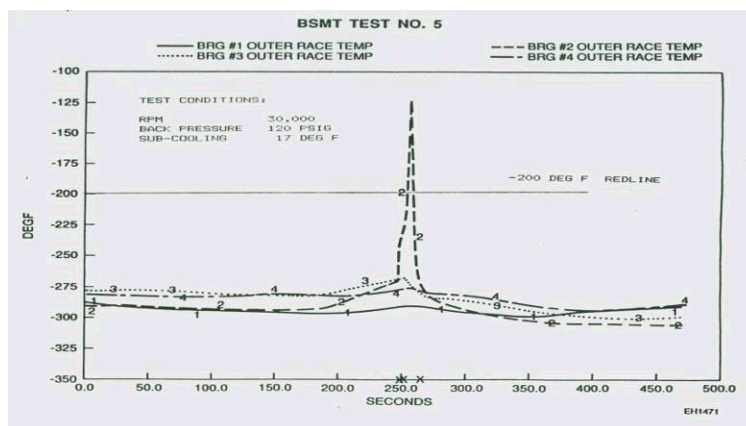
BSMT AFTER LOX FIRE. BSMT WAS REBUILT AND BEARING TESTS WERE RUN IN LN2 FOR SEVERAL YEARS BEFORE RETURNING TO LOX TESTS



HEAVILY WORN BEARING FROM THERMAL MARGIN TEST. THIS BEARING HAS HIGH THRUST LOADING DURING RUNS. MAJOR SURFACE DISTRESS ON RACES, CAGE DAMAGED, AND SEVERELY WORN STEEL BALLS



LOW THRUST LOADED BEARING FROM BSMT. CAGE NOT DAMAGED, MINOR SURFACE DEGRADATION ON RINGS, BALLS SLIGHTLY WORN



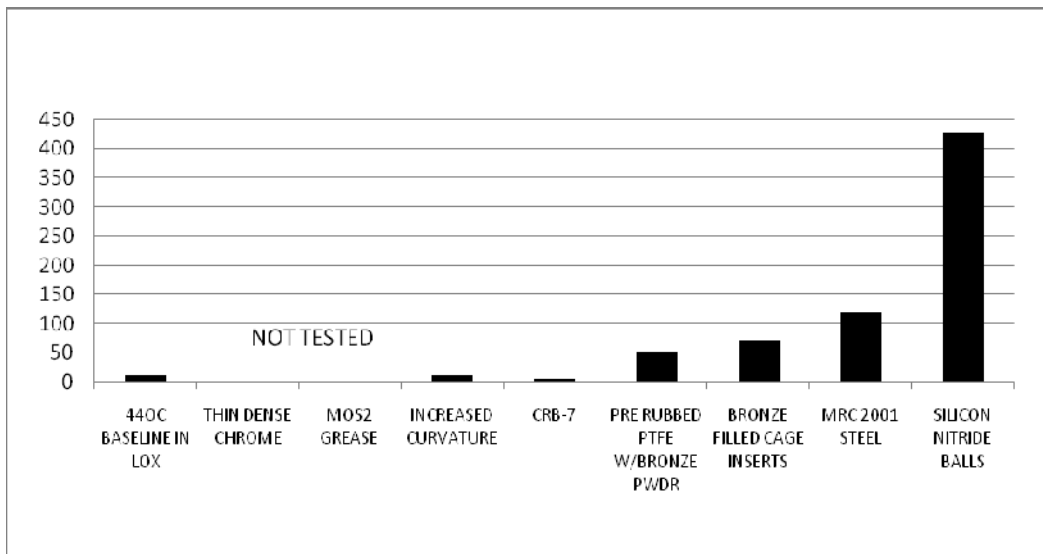
BEARING OUTER RACE TEMPERATURE DATA PLOT BEARING HEAT GENERATION IS GREATER THAN THE COOLANT'S CAPACITY TO REMOVE THE HEAT, RESULTING IN A SUDDEN INCREASE IN TEMPERATURE



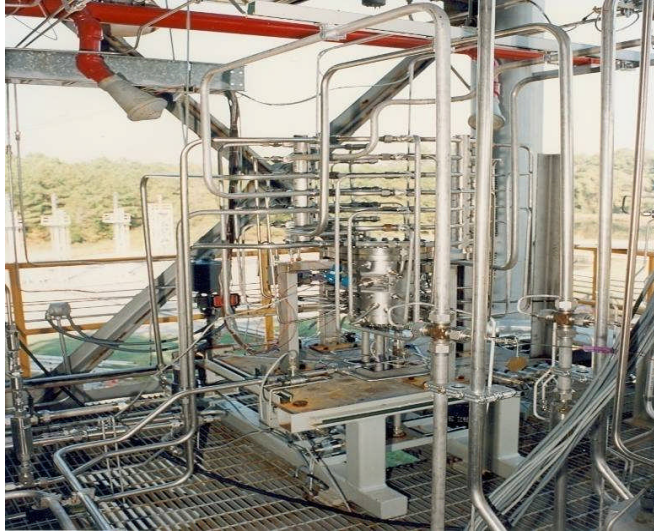
SSME HPOTP BEARING WITH SILICON NITRIDE BALLS AS RUN IN THE BSMT



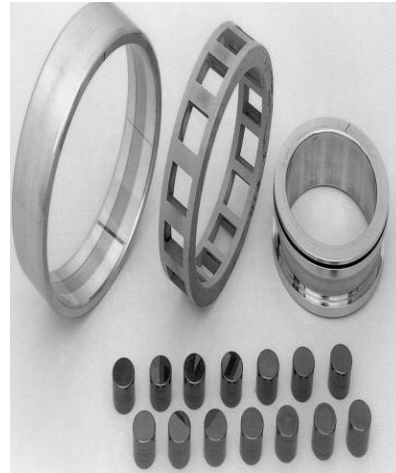
BEARING CAGE WITH BRONZE POWDER/PTFE INSERTS AND BRONZE HOUSING TESTED IN BSMT



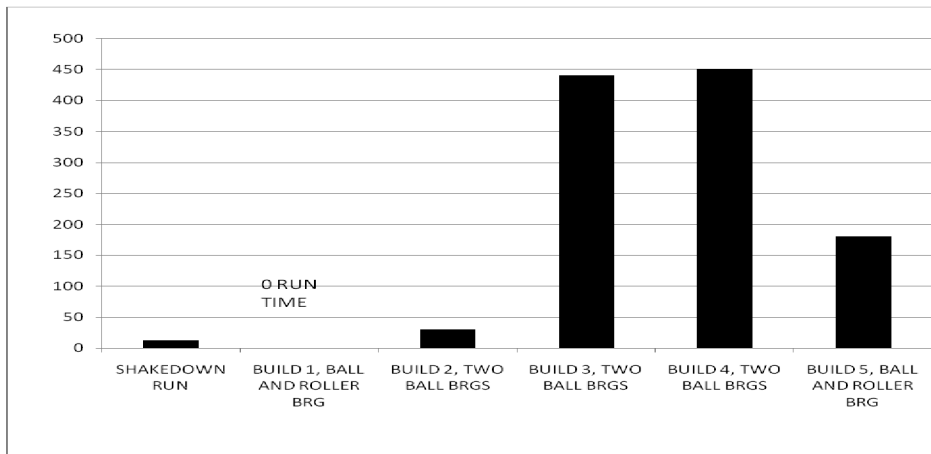
SELECTED BEARING TEST TIMES IN THE BSMT. SILICON NITRIDE BALLS SHOWED 40X GAIN IN RUN TIME OVER BASELINE BEARINGS



LH2 BEARING RIG ON TEST STAND. THIS TESTER WAS BUILT TO TEST P&W BALL AND ROLLER BEARINGS

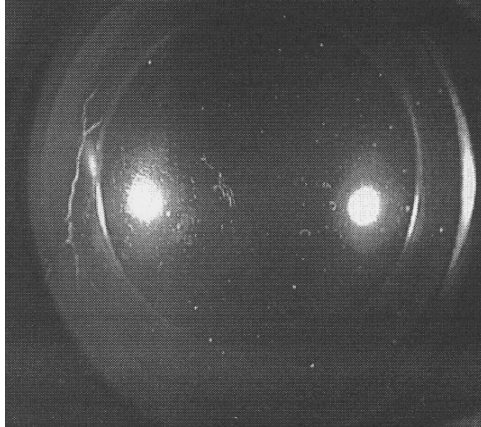


PRATT AND WHITNEY SSME BALL AND ROLLER BEARINGS TESTED IN THE LH2 RIG

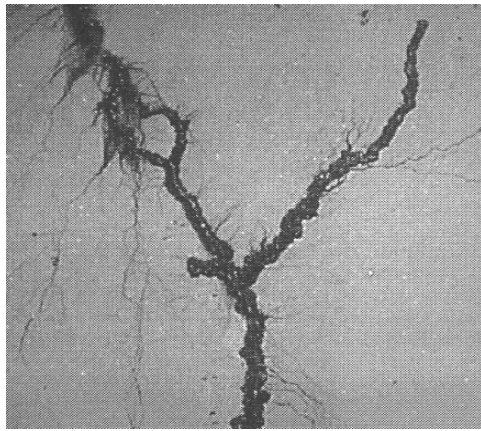


RUN TIMES ON BUILDS OF THE LH2 TEST RIG

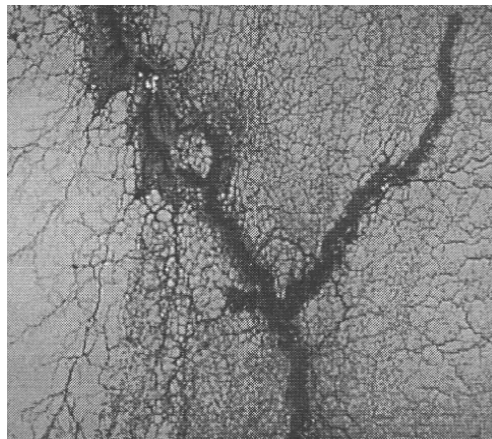
RIVER MARK ANOMALY AS SEEN ON SILICON NITRIDE BALLS



**RIVER MARK ON LEFT SIDE OF BALL AT
START OF TESTING IN LH2 RIG**

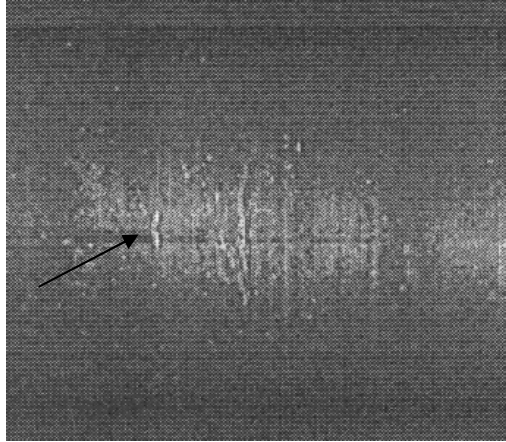


CLOSE UP OF RIVER MARK PRE TEST



**RIVER MARK AT 3 HOURS SHOWING MAIN
ANOMALY NOT DEGRADING BUT SURFACE
CRAZING HAS FORMED AROUND THE MARK**

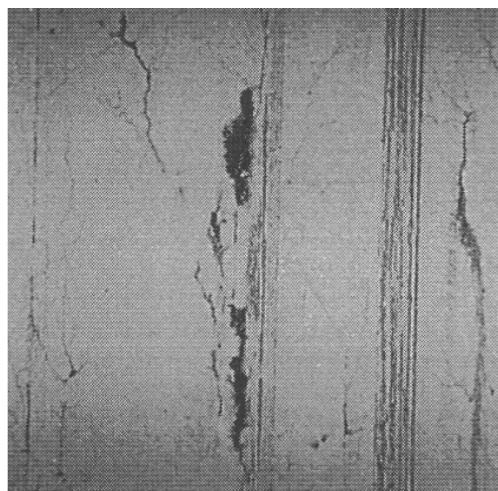
FEATURES SEEN ON SILICON NITRIDE ROLLERS IN LH2 RIG



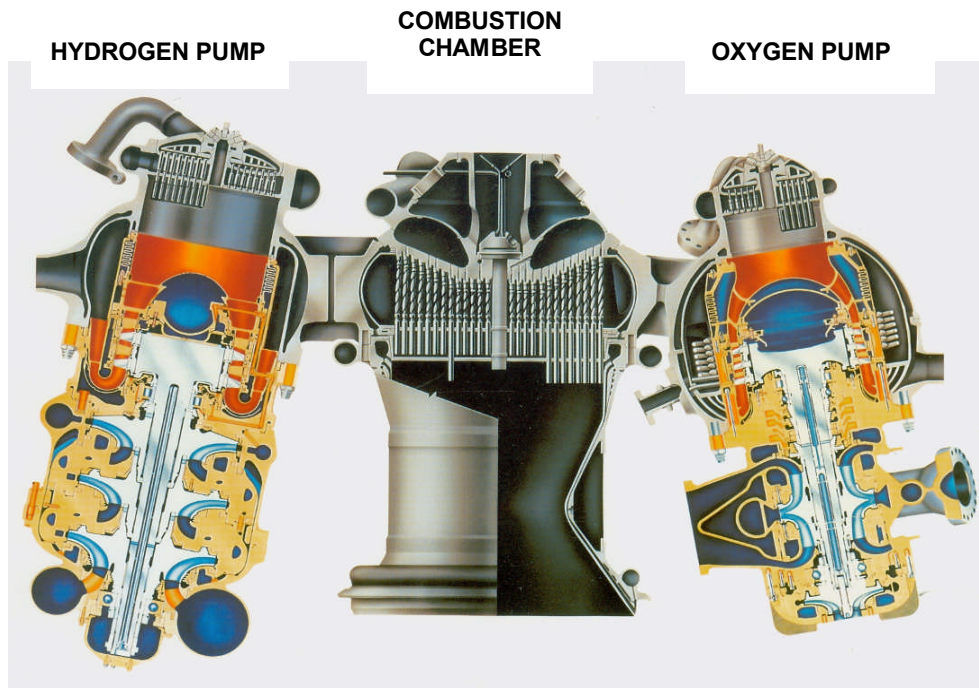
SURFACE FEATURE LEFT OF CENTER ON ROLLER



CLOSE UP OF SURFACE INDICATION PRE TEST



SURFACE AFTER 3 HOURS SHOWING LESS SURFACE DEGRADATION THAN SEEN ON THE BALLS FROM SAME TEST



THE SPACE SHUTTLE MAIN ENGINE HIGH PRESSURE TURBOPUMPS ARE SUCCESSFULLY RUNNING HYBRID BALL AND ROLLER BEARINGS. THESE BEARINGS WERE PROVEN TO BE DURABLE AND ROBUST IN THE BEARING TEST PROGRAM AT MSFC.



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC

History of Space Shuttle Main Engine Turbopump
Bearing Testing At The Marshall Space Flight Center

Howard Gibson, Robert Thom, Chip Moore, MSFC
Dave Haluck, Pratt & Whitney

Materials and Processes Lab, Mechanical Test Branch, Tribology Team
JANNAF conference, May 2010



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC

Shuttle uses 2 solid rocket motors and 3 liquid fed main engines for launch

Each main engine has 2 low pressure and 2 high pressure turbo pumps for sending propellants to combustion chamber

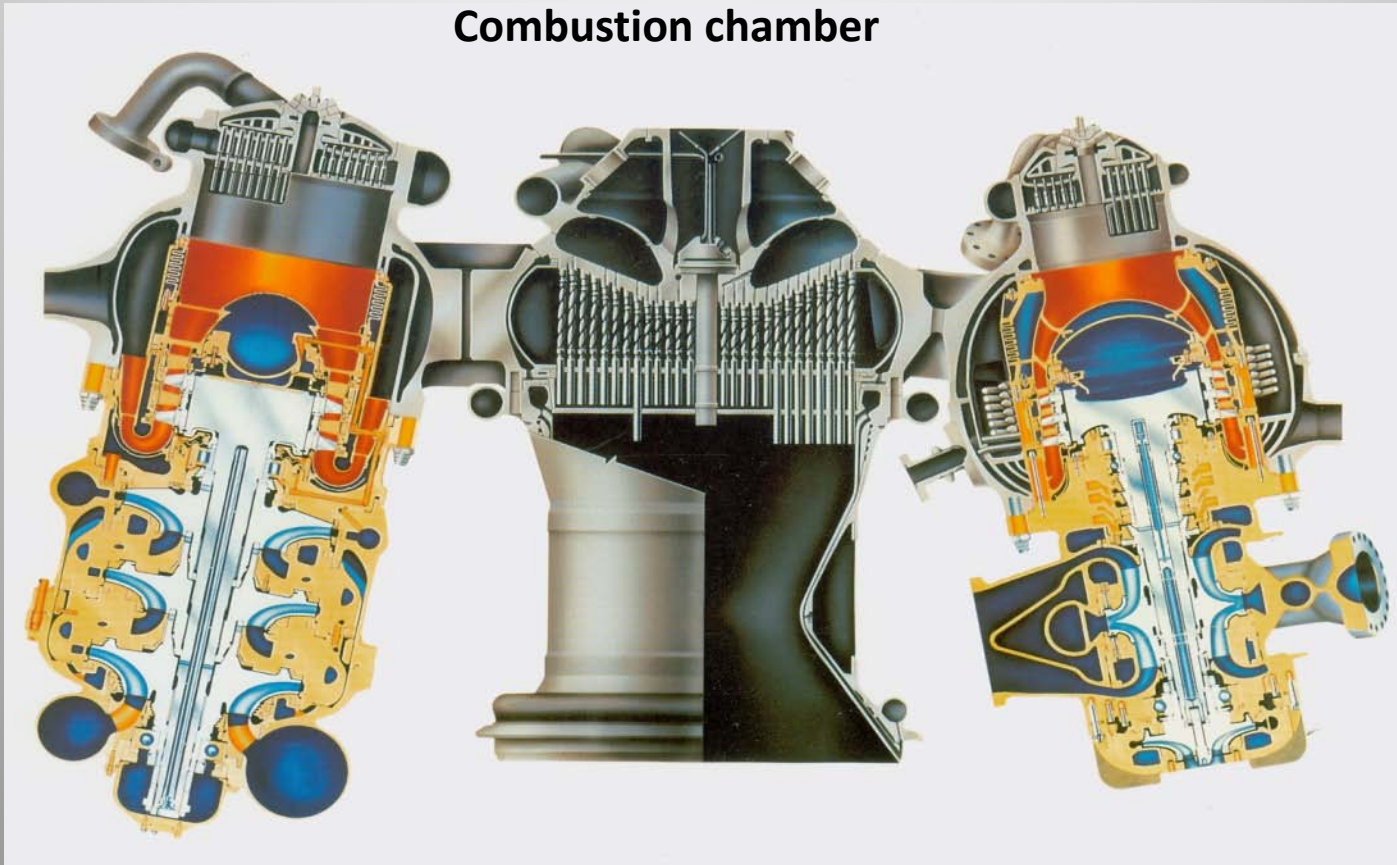




SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC



Combustion chamber



High pressure hydrogen turbopump

High pressure oxygen turbopump



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC

- In the late 1970's, the high pressure lox turbopump (HPOTP) was not meeting its 55 flight life goal
 - Main shaft bearings were a major contributor
- No consensus in the bearing community as to the cause of the bearing failures
 - Wear , internal heat generation, inadequate coolant properties, radial and thrust loads, bearing geometry, combination of all?
- MSFC team was directed to develop a bearing test program to investigate bearings in the turbopump environment
 - The Bearing and Seal Material Test program was conceived and tests began in 1982
 - Commonly referred to as the BSMT program



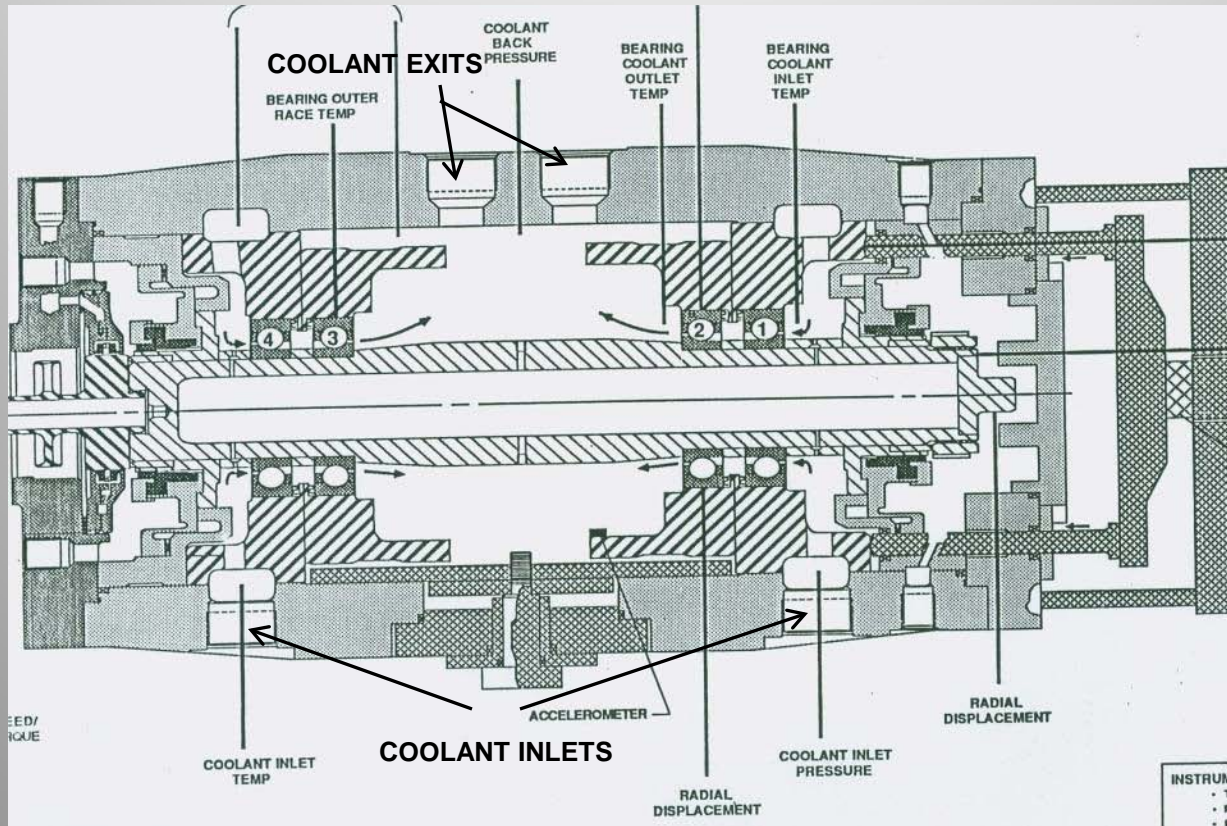
SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC

- **BSMT designed to test 4 Rocketdyne HPOTP bearings**
 - 440C steel rings and balls, PTFE/glass fabric cage
- **Mounted in pairs, back to back with preload**
- **Tester duplicated turbopump environment as closely as possible**
- **Instrumentation installed for pressures, temperatures, speed, accelerations, and displacements**
- **Data collected and plotted out for analysis after each test**
- **Borescope inspections performed between each test**
- **Test stopped when bearings reached unsafe run condition**
 - Balls sliding in races, cage damage, inner race upper shoulder wear, test cut by redlines, test time very short
- **SRS Technologies (now NeXolve) brought in as a consultant to run bearing analysis and support testing – SHABERTH bearing and SINDA thermal computer codes used**



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC

Cross section of BSMT



Drive end,
450 HP
diesel thru
speed
increaser to
30,000 rpm,
1.7M DN

Load end, axial
load cylinder

Radial load cylinder, not
shown



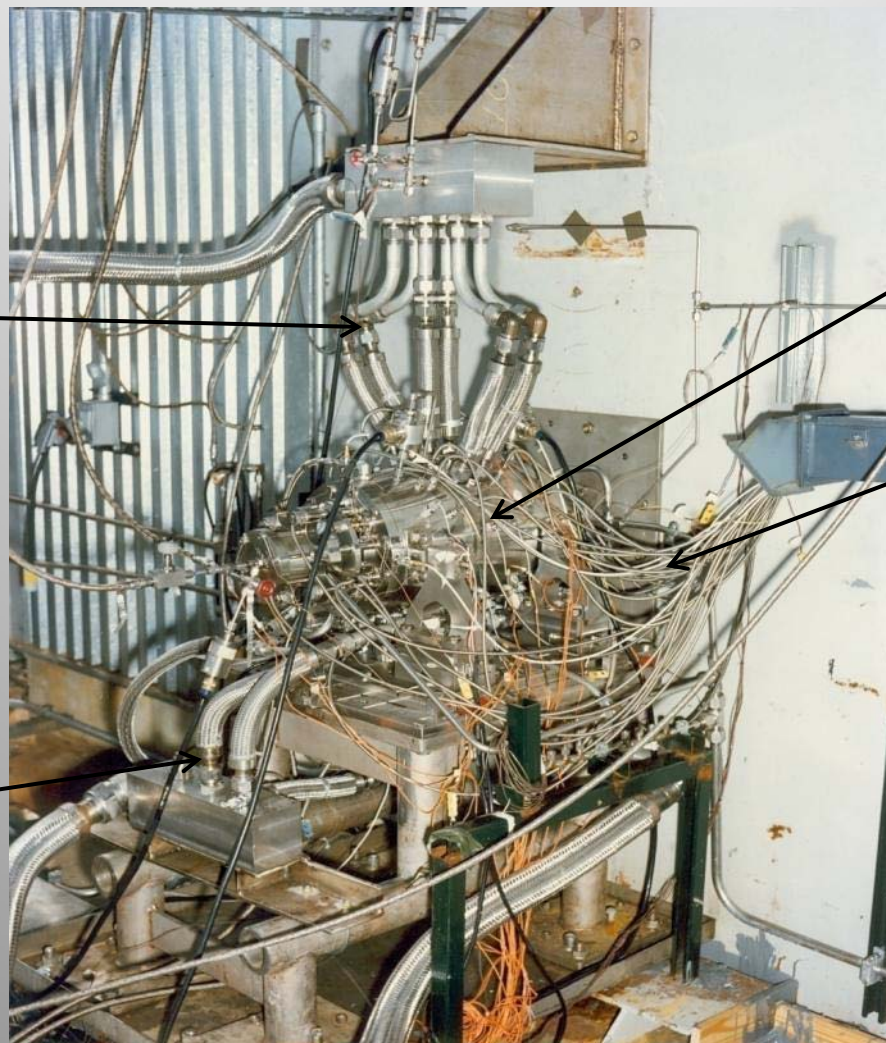
SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC

BSMT on test stand

Outdoor test facility

Coolant exit lines

Coolant inlet lines for LOX



Test rig

Instrumentation cables

Drive train behind wall



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC

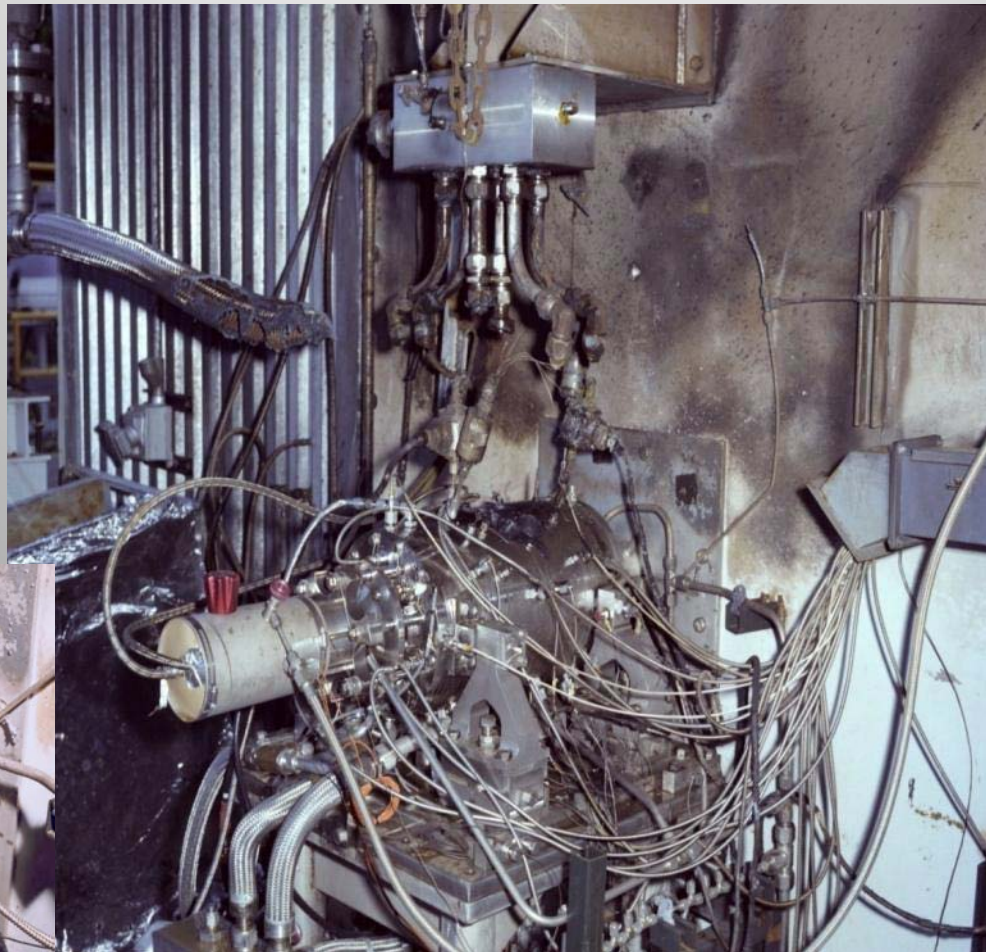


!!!LOX FIRE!!!

Loss of coolant
thru bearings in
one end of rig
leads to fire

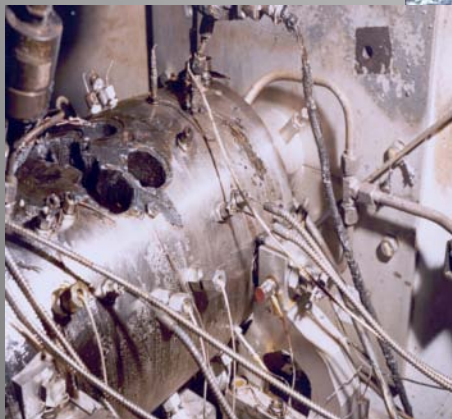
Fire suppression
system
extinguishes fire

Inconel
housing



Stainless steel
braided hoses
gone, housing
burnt thru

Test were run in
LN2 before going
back to LOX

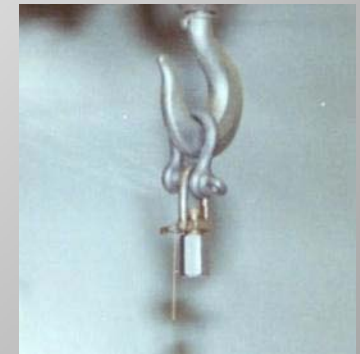
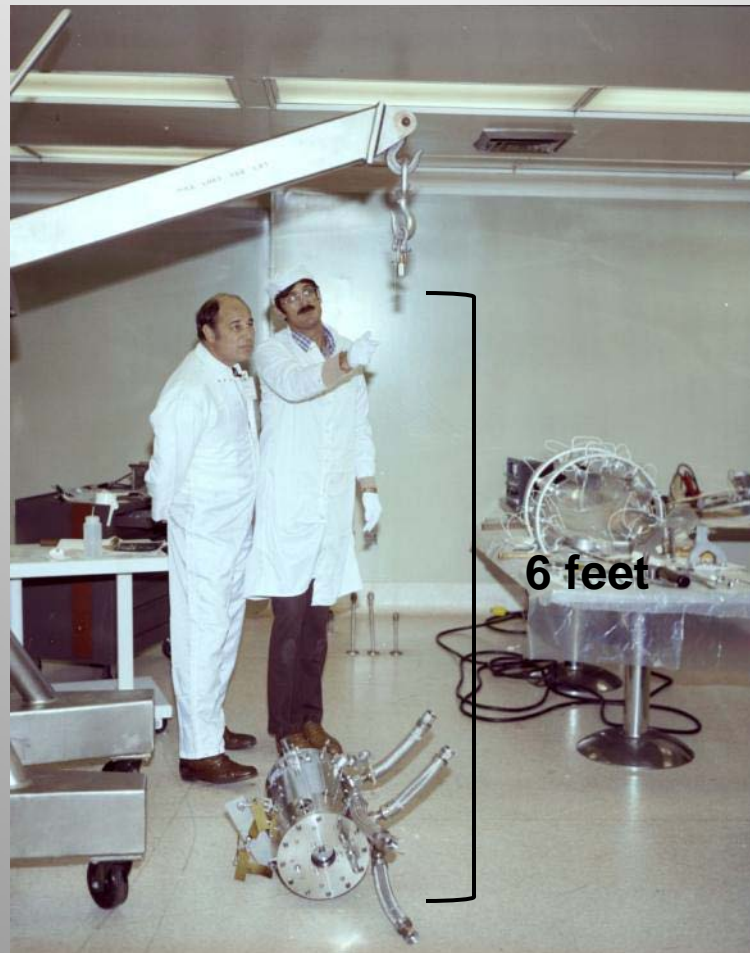




SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC



A LOX fire is not the only hazard when building test rigs



BSMT was being spun around for final assembly. Swivel fitting did not work. Eyebolt came loose and rig fell to floor. This build was not sent to test stand.



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC



- **BSMT test program and results**
 - **Coolant flow rate investigation**
 - **Bearings ran until surface distress visible and run time short**
 - **Doubled coolant flow rate**
 - **Allowed bearings to run slightly longer but continued to wear**
 - **Sub-cooling margin tests (below saturation line at test P and T)**
 - **Sub-cooling margin of coolant lowered until thermal runaway occurred**
 - **Sudden temperature increase seen in two bearings on two separate test**
 - **Data showed sudden temp increase around 17 degree sub-cooling**
 - **Correlated closely to SHABERTH/SINDA prediction of 13**
 - **Large amount of bearing distress seen**
 - **Inner race upper shoulder rough, balls not round, cage pockets damaged, spalling of inner race**
- **BSMT bearings similar to those seen after hot fired turbopump runs**



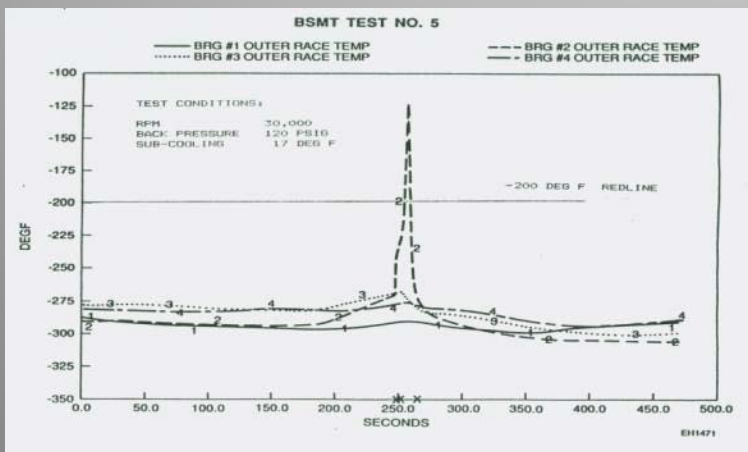
SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEC



Heavily worn born bearing from margin test, high thrust load



Bearing from margin test, low thrust load

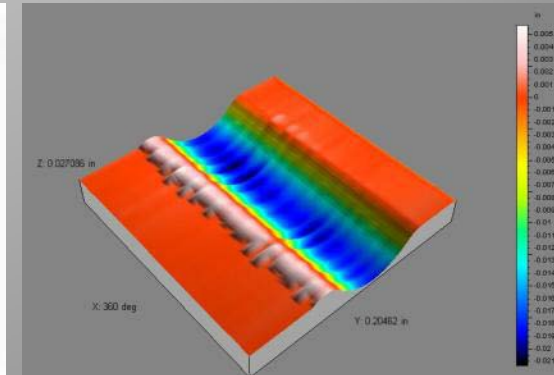
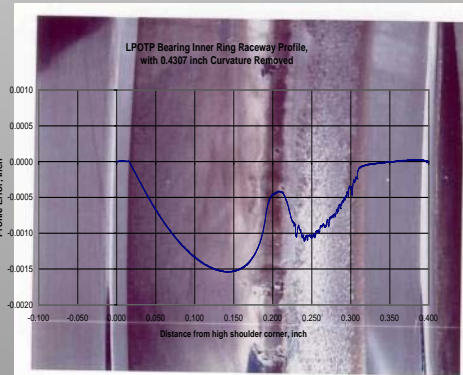
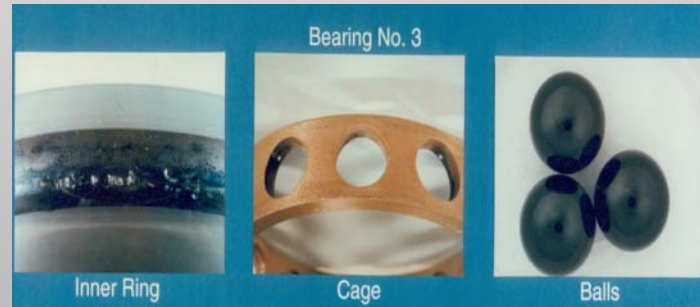
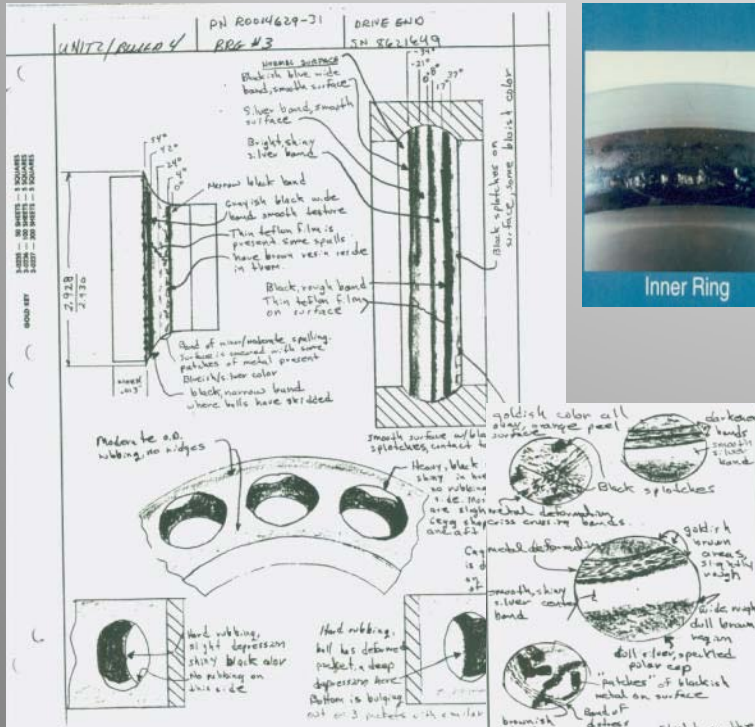


Bearing OR temperature plot - heat generated in bearing greater than the coolant's capacity to remove the heat - results in sudden increase in temp. or thermal runaway



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEC

- First bearing inspections were sketched on paper, later upgraded to Polaroid instant film camera, hand held measuring instruments used
- Tribology Lab now has Taylor Hobson surface metrology equipment, HD video, micro inch measurement capability , 3D microscope w/display, many years of experience in metrology, purchases funded by SSME





SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC

- Investigate lowering heat generation in the bearing
 - Filled cages with LOX compatible oil
 - Bearings showed distress earlier than standard cage
 - Thinking was the oil froze and acted as an abrasive
 - LOX compatible grease rubbed in ball pockets
 - High concentration of MoS₂ in a paste rubbed in pocket
 - Cannot control the amount of grease very well
 - Grease spread during balancing operations, could not balance assy
 - Opened up inner ring curvature to decrease heat generation
 - Hertzian contact stress goes up
 - No improvement
 - Burnishing of bronze filled PTFE on rings before tests
 - Application process difficult and not repeatable
 - BSMT ran 51 minutes, 5X life improvement over baseline LOX time of 10 min



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC



- **Carbon fiber cages**
 - **Light weight, PTFE coated layers**
 - **Found voids in fabric, layer separation, very fragile**
 - **Never installed in bearings**

- **Thin dense chrome (TDC) plated on rings for wear resistance**
 - **Four bearings sent to vendor for application**
 - **Installed in balance assembly**
 - **During balancing, large amount of heat generated and shaft locked up**
 - **Never installed in test rig**



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEC

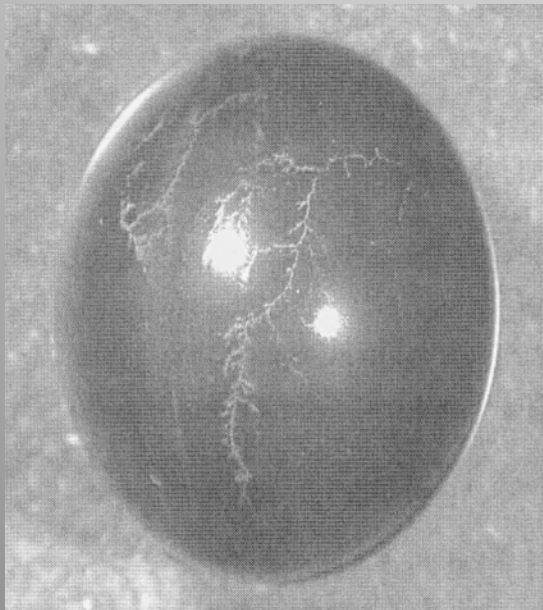
- **New materials were being developed by bearing manufacturers**
 - **CRB-7 powder metal steel, MRC 2001 powder metal steel, Cronidur 30, Silicon Nitride rolling elements**
 - **CRB-7 bearings installed in BSMT, ran for 6 minutes**
 - **Cronidur 30, came along later, not tested in the BSMT**
 - **MRC 2001 bearings gave a 10X life improvement**
 - **Would have received more interest if not for results w/Silicon Nitride**
 - **Silicon nitride rolling elements, 0.5” diameter balls**
 - **Obtained from domestic and foreign suppliers**
 - **Direct replacement for the 440C balls**
 - **Immediate gain in bearing life and overall performance**
 - **no temperature spikes during runs, ran to LOX tank depletion, very little ball wear,, light cage pocket contact, no IR upper shoulder contact, no OR negative angle contact, some surface distress on IR**
 - **Last tester build gave 40X life improvement over LOX baseline**
 - **Saw “river marks” on the surface of the balls**



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC



- **River Marks –**
 - **Characterized by width greater than depth, flat bottom surface, sharp broken edges on top; Not a crack!**
 - **Grew in length and number of branches as time accumulated on rolling elements**
 - **Cause is not known, only seen in cryogenic bearings, no failures seen in testing**





SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC

- **Silicon nitride rolling elements isolate rotor from ground**
 - **Electrical arcing occurs across narrow gaps from rotor to housing cause pitting**
 - **Seen in test rigs at MSFC**
 - **Consideration should be given in the design process to ground the rotor**



**SSME HPOTP
bearing w/ silicon
nitride balls**



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEFC



- **New cage material and design developed by Battelle Labs**
 - **Bronze powder filled PTFE inserts held in place by a brass housing**
 - **Insert material not structurally sound to be the entire cage**
 - **Inserts eliminate glass fibers in the current cage design – reduce heat**
 - **Cages installed into bearings and run in BSMT**
 - **Bronze transfer film seen on balls after test runs**
 - **Gained 7X run time in Rocketdyne bearings over standard cage**





SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC



- **BSMT had proven new bearing technologies to be useful in SSME application**
 - **How to get them into a pump?**
- **The Technology Test Bed (TTB) program came to MSFC**
 - **Space Shuttle main engine hot fired in the east test area**
 - **Gave bearing team a chance to run improved technology from BSMT testing**
 - **How to convince skeptics of Silicon Nitride's robustness and durability?**
 - **Had completed ~10 hours of Silicon Nitride ball testing at 377 ksi Hertzian contact stress, 12 bearings tested**
 - **TTB qualifier test ~ 4 hours at 493 ksi contact stress with axial and radial loading and simulated transient thrust loads, 8 bearings tested**
 - **No failures , What other test could be done?**



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEC



THE 1-1/2 POUND HAMMER TEST!!!



- Took the hammer and ball to program managers and let them take a swing
- One bearing with silicon nitride balls was successfully run in a HPOTP in the TTB!!
- The BSMT bearing tester was retired in 1994 after 12 years of service



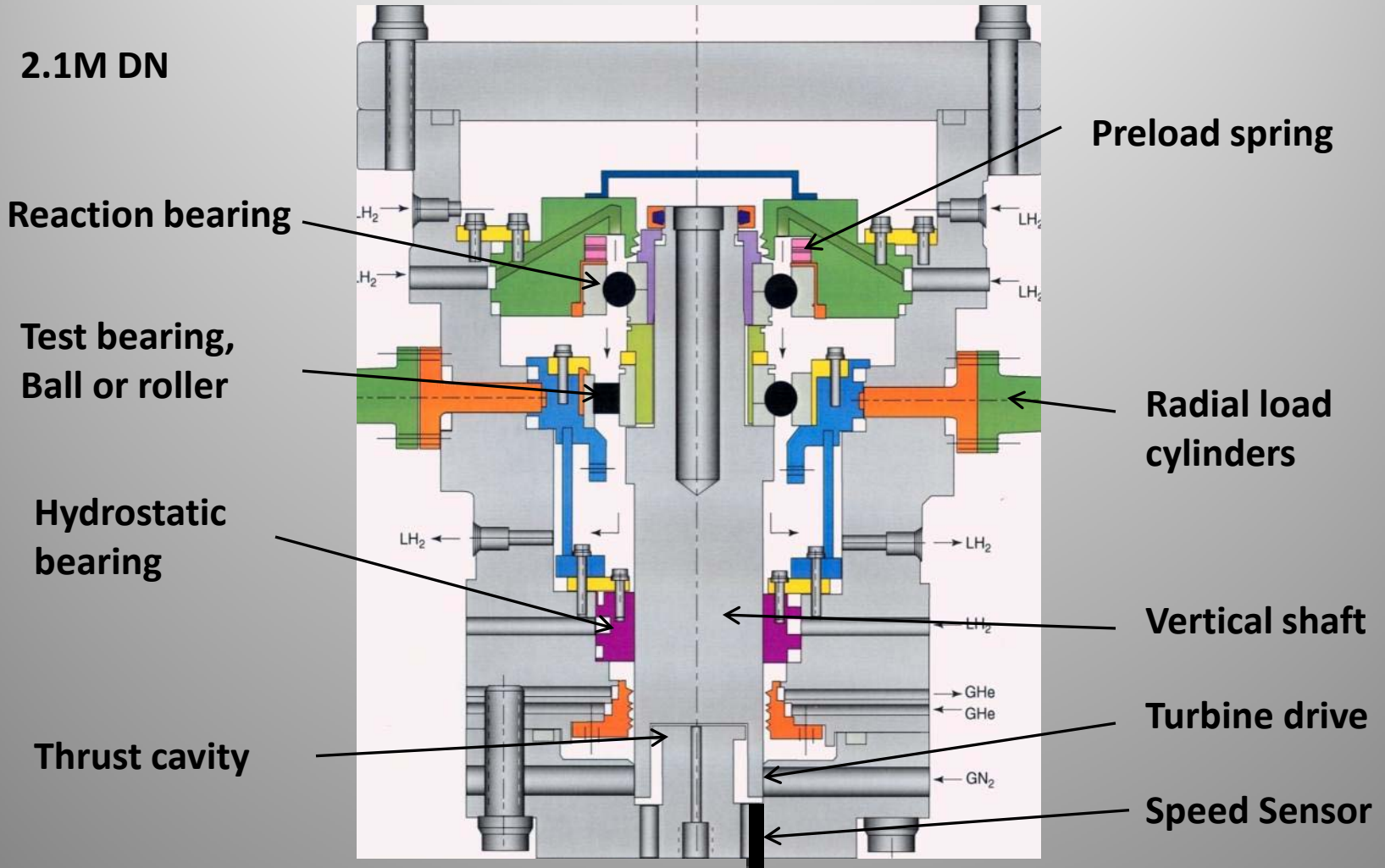
SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC

- Bearing team at MSFC became interested in testing hydrostatic bearings for future high speed turbopumps
- Test rig was designed , fabricated, and delivered to MSFC, named LH2 test rig
- Around this same time, Pratt & Whitney had become the supplier of the SSME high pressure pumps
 - Bearings from pump testing were showing river marks on the rolling elements
 - Pratt needed to investigate the long run time durability of balls and rollers with river marks in hydrogen environment for validation of bearings
 - LH2 test rig went thru a redesign for testing rolling element bearings
 - Pratt was using Cronidur 30 steel, silicon nitride rolling elements, bronze/PTFE cage inserts (their own design)
 - SRS on board to build computer model for roller/ball bearing testing
 - ADORE bearing model delivered to MSFC for dynamic bearing analysis



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEC

LH2 test rig





SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEC

LH2 tester on stand



**Hydrogen burn
stacks**



**Inlet and exit tubing
above rig for access to
instrumentation**



Test rig





SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEC

- **Shakedown Run of LH2 rig**
 - Two ball bearings, one with 440C balls, one with SiN balls
 - Test rig top and bottom pressure control issues causing shaft axial movement position problems and speed problems, coolant level tank sensor, tank leaks,....
 - Managed to run 12 minutes at 35,000 rpm
- **Build 1.0 – ball bearing and roller bearing in test position, SiN elements**
 - Three attempts to run, last attempt showed no rotation on speed sensor
 - Shaft axial position not controllable, speed indications not reliable
 - Pulled rig – bottom of shaft and top of thrust cavity had heavy rubbing



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEC

- **Decision to go back to ball bearings for Build 2, SiN elements**
 - **Changes made to facility controls for better shaft axial position pressure control....**
 - **During leak check, over stressed bearings to 687 ksi**
 - **Brinelling expected on races - found post test with Talyrond, not deemed significant to degrade performance of bearings**
 - **Attempted 4 runs, stopped, performed a pressure calibration to get an understanding of how internal pressures affect the shaft position**
 - **Incorporated automated shaft pressure control into test procedure**
 - **Next 4 runs were excellent**
 - **Accumulated 30 minutes at 35000 rpm**
- **Results of bearing inspections showed no evidence of anomalous wear modes that were not seen in engine testing.**

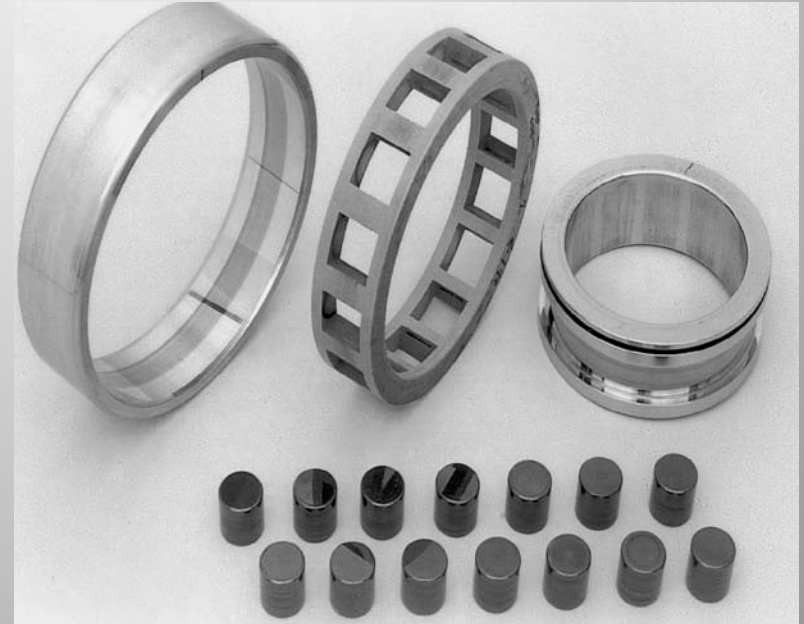


SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEFC

Bearings for testing in the LH2 tester



Ball bearing with silicon nitride balls



Roller bearing with silicon nitride rollers



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEFC

- **Build 3 of LH2 rig, SiN elements**
 - **Goal was to establish the durability of SiN elements with river marks on balls using a heavily marked bearing from engine testing**
 - **Was most heavily marked bearing from engine tests**
 - **Mapping of ball features done pre and post tests**
 - **Applied axial load cycles to simulate transient loading - 5000 lbs each cycle**
 - **Ran 7.33 hours total time at 35000 rpm, 120 axial load cycles**
 - **Bearing inspections showed that the main river marks did not increase in area or depth, but smaller tributaries grew away from the main indications**
 - **Wear on other bearing components was moderate, debris denting on races cage pocket rubbing, ..**



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEFC

- **Build 4 of LH2 test rig**
 - **Comparison of domestic SiN with Japanese SiN balls and formation of river marks**
 - **New balls from both suppliers installed in bearings**
 - **Ran 32 runs, 126 thrust load cycles of 6,100 lb , 7.5 hrs total time**
 - **River marks seen on both bearings after 4.3 hrs.**
 - **Marks resembled high time engine fired bearings**
 - **This build plus #3 has shown that the bearings are capable of meeting the 60 mission design life**
 - **Had run bearings with hot fire engine time w/ river marks**
 - **Had created river marks on rolling elements in bearings**
 - **No failures, bearings in good condition**

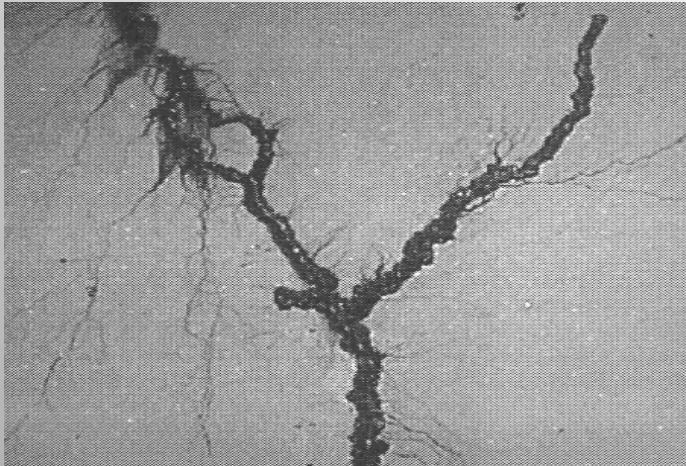


SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEC

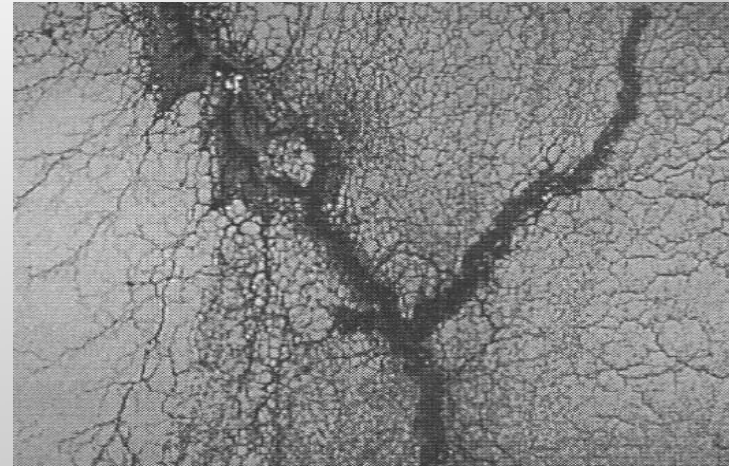
- **Build 5 of LH2 rig, previous tested SiN elements**
 - 18 hours of test rig experience, axial shaft control good, no speed issues
 - Went back to roller bearing in test position
 - Attempted runs, had problems again... shaft movement and speed
 - test procedure modified as to when and how much radial load was applied
 - Ran 11 tests for ~3 hours, on 12th run - tester shaft would not rotate
 - Roller skewing in cage pockets?
 - Decided to pull rig and inspect
 - No evidence of roller skewing detected
 - Balls had a crazed look on the surface, moderate cage pocket wear
 - Rollers looked good with slight increase in surface distress, some mild rubbing on the ends by cage contact
 - Cage pocket wear moderate



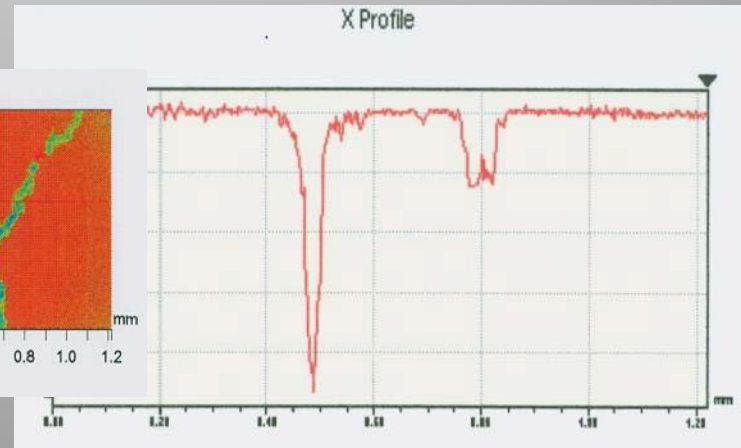
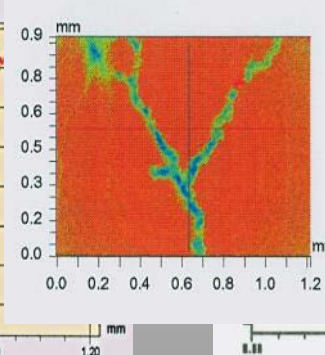
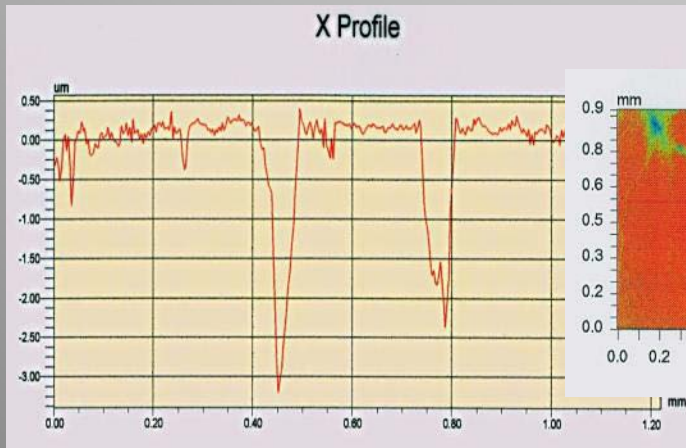
SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEC



Pre test river mark on ball, Build 5

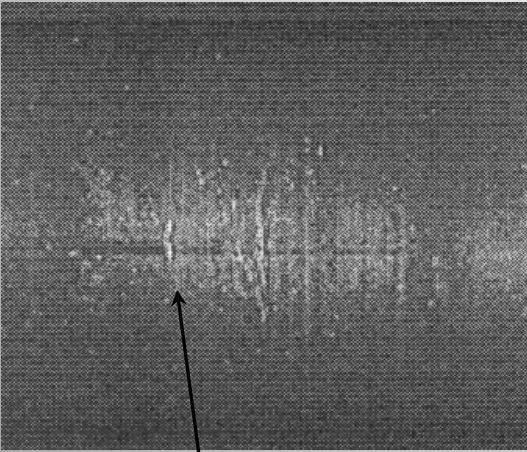


River mark at 3 hours run time





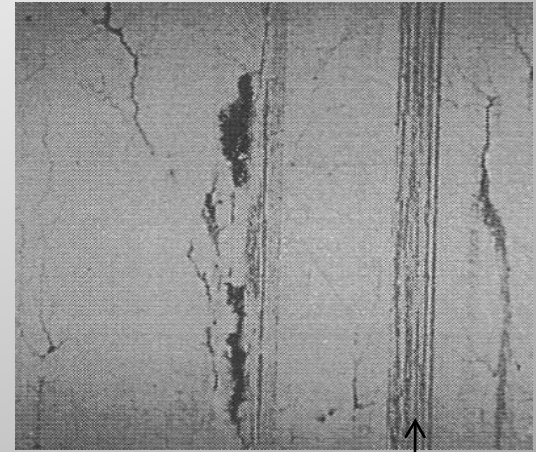
SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEC



Surface of silicon nitride roller, mark of interest



Close up of feature, pre test



CAGE RUBBING ON ROLLER

Mark after 3 hours of run time



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSEFC



- **Decision was made not to rebuild test rig based on test area schedule and time accumulated on the hybrid bearings**
 - **The LH2 rig completed 6 builds, 8 bearings tested, ~21 hours run time**
 - **Bearings in test rig experienced excessive speed, major speed fluctuations, high radial loads, 120 thrust cycles representing transient loads.... and all survived!**
 - **2 test runs met 60 mission life times without failures – proved durability of silicon nitride in P&W turbopump environment**
- **Pratt & Whitney is successfully running hybrid bearings in the SSME high pressure pumps today**
- **Test rig retired in February 1999**



SPACE SHUTTLE TURBOPUMP BEARING TESTING AT MSFC



- **Concluding remarks;**
 - **17 years of bearing testing has led to better knowledge of bearing behavior in turbopump environments; what bearing materials work and which do not; the development and validation of computer analysis models for bearings in test rigs and turbopumps and knowing that NASA is flying the best bearings to ensure the success of its missions now and in the future.**
 - **Bearings with Cronidur 30 rings and silicon nitride rolling elements are commercially available from Barden/FAG. Bronze powder filled insert cages not available - specific to cryogenic/SSME applications.**
- **Special thanks to the SSME project office for funding the bearing test program through the years that gave meaningful results back to the aerospace community and to Fred Dolan, MSFC , who was the driving force behind the BSMT bearing testing program**



- **Silicon nitride balls on hand**