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PRATT & WHITNEY CRYOGENIC TURBOPUMP BEARING EXPERIENCE

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ABSTRACT

Pratt & Whitney's active participation in rocket engine turbopump development dates from the 1950's. Reliable bearings are imperative, therefore, the early development effort included substantial design and development testing of long life, reusable, rolling element bearings in cryogenic fluids. Successful, reusable bearings require lubrication, traditionally, a transfer film from sacrificial cage wear. Early testing included materials screening programs to identify suitable cryogenic cage materials. A specially developed element tester that simulated the function of a ball bearing cage was used. Suitable materials must provide lubrication with an acceptably low wear rate, without abrading contacting surfaces. The most promising materials were tested in full scale bearings at speeds up to 4 MDN. Teflon, filled with 40% bronze powder, was the best performing material. A variety of bearings were designed and successfully tested in LH_2 and LOX. Bearings with bronze filled Teflon cages were successfully tested for 150 hours. In overload tests, the same design was tested for 5 hours at maximum Hertz stresses above 450 ksi and an additional 5 hours with a maximum Hertz stress exceeding 500 ksi. Four bearings were tested in LOX for 25 hours, with a maximum time per bearing of 10 hours.

BACKGROUND

RL10 development started in the late 1950's. This was to be the first liquid hydrogen/oxygen space propulsion system. It was recognized early that reliable cryogenic bearings would be required for practical turbopump systems. Rolling element bearing testing started in 1958 and by the end of March 1959, there had been 58 test rig runs with total accumulated time of 287 hours. This testing verified the feasibility of operating rolling element bearings in LH_2. However, it was evident that better retainer materials and designs were required. Early retainers used Teflon, Kel-F and Rulon A (a silicon filled Teflon). This early testing showed that retainer structural integrity and appropriate cage/guide land clearance definition was necessary for successful operation.

RL10 DEVELOPMENT TESTING

The RL10 engine program continued active bearing development. Program objectives included endurance demonstrations and off design performance and margin verification and alternate materials investigations.

The RL10 engine uses a turbine driven LH_2 pump with a gear drive to the LOX pump, all bearings operate in a hydrogen environment. Turbine and pump interstage bearings operated at 30,000 rpm and support a 600 lb. thrust load and are cooled with LH_2 at a temperature of 50 - 75 R. In addition, there is an idler gear that operates at 12,000 rpm with 1000 lbs. radial load. The LOX pump also operates at 12,000 rpm and uses similar bearings. A 35 x 62mm split inner ring angular contact ball bearing with a metal shrouded, filled Teflon, retainer is used on both shafts and was the development test article.

Substantial endurance test times have been accumulated on LH_2 cooled bearings to demonstrate bearing reliability and define margin. Maximum time for a single bearing is a total test time of 150 hours, this consisted of 75 hours at the LH_2 pump conditions of 30,000 rpm and 600 lbs. axial load and an additional 75 hours at the LOX pump conditions of 12,000 rpm and 150 lbs. axial and 500 lbs. radial load. Two other bearings were tested for 36 hours each, 5 bearings were tested for 25 hours each, and 6 bearings were tested for 12.5 hours each, all at the LH_2 pump conditions.

Overload capability was also demonstrated by rig testing. A bearing was operated for 5 hours with an axial load of 1000 lbs., which resulted in a maximum Hertz stress at the ball/race contact greater than 450 ksi. This same bearing was then tested an additional 5 hours with an axial load of 1500 lbs., resulting in a maximum Hertz stress greater than 500 ksi.

Overspeed margin was demonstrated with 2 bearing tests, each at 40,000 rpm. Both bearings demonstrated lives exceeding 5 hours. In addition, a bearing with a specially designed Salox M retainer was tested at 50,000 rpm for 25 min. The test summary indicates there was some ball pocket wear but was otherwise successful.

Baseline RL10 bearings used AMS5630 (440C) rings and balls with an aluminum shrouded Rulon A retainer. Alternate materials were evaluated for rings and balls, and retainers. Some candidate materials are shown in Table 1.

TABLE 1

	Rings & Rolling Elements	Retainers
Candidate Materials	AMS5628	Al shrouded Salox M
	AMS5616	bronze
	AMS6260	Inconel
	Haynes 25	BeCu
		AISI 303

The various candidate ring and rolling element materials were evaluated with five 5-minute endurance cycles. All candidate materials, except the Haynes 25 successfully passed this demonstration test, however, none showed an advantage over the baseline AMS5630. Most of the metallic retainer materials performed satisfactorily for short duration tests (approximately 1 hour) when coated with a dry lubricant or plated with silver and lead. However, bearings with Salox M retainers demonstrated excellent performance.

Other tests, intended to verify design margin, included misalignment demonstrations at 10' and 20' angles, contamination with metallic cutting chips, deliberately weakened cage and reduced coolant flow.

ALTERNATE CAGE MATERIAL DEVELOPMENT

This early testing during RL10 engine development identified the retainer design and material selection as critical to successful performance. Therefore, we initiated a retainer development program intended to identify materials that would satisfactorily lubricate ball bearings in LH_2 at speeds up to 4 million DN (DN is an application severity parameter and is the product of the bearing bore diameter in mm and the inner ring rotating speed in rpm). This initial program evaluated 21 different retainer material candidates in a retainer simulator rig, figure 1.

The retainer simulator is a ball plate rig using counter-rotating plates to achieve the high ball rotational speed without high centrifugal loads. One plate was vee-grooved and the other flat, this induced a ball spin component equivalent to a typical bearing application. Test tracks were located at 2 radii to simulate either 2 or 4 MDN. Ball to plate loads were selected to result in a maximum contact stress of about 450 ksi. The test section was isolated and maintained in an LH_2 environment during all candidate testing.

All candidates are listed in Table II with a brief summary of performance. A typical after test photo, figure 2, shows the candidate material retainer insert in the rig retainer with test induced pocket wear. The four best performing candidates were Salox M, a bronze powder filled Teflon; Rulon A, a silicon filled Teflon with MLF-5 solid film coating on the races; bronze filled polyimide and $Ag\text{-}WSe_2$ filled polyimide.

Full scale test bearings were fabricated with retainers made from each of the four best performing candidate materials. This bearing was an 80mm bore diameter split inner ring angular contact ball bearing. These bearings were tested at speeds up to 50,000 rpm, which is 4 MDN. Bearings with Salox M retainers performed best and did operate successfully at 4 MDN for a few minutes.

LOX PUMP BEARING DEVELOPMENT

Later pump development programs required LOX cooled ball bearings which lead to design and demonstration testing in a LOX environment. A 50mm bore diameter split inner ring angular contact bearing with an aluminum shrouded Salox M retainer was designed.

A test rig similar to that used for the 35mm bore RL10 testing was designed and built. This rig is shown schematically in figure 3, and actual rig hardware is shown in figure 4. After rig checkout with LN2, LOX testing began and continued for four rig builds with a total LOX time of 25 hours. All rig builds were successful and maximum time for a bearing set was 10 hours. Figure 5 shows the speed, load and coolant flow profile during the 10 hour test. For the last 5 hours, speed was constant at the full design speed of 24,000 rpm. At that speed, 5 lbs/min. of LOX was provided for cooling. This unusually low coolant flow was arrived at by reducing the flow until the LOX vaporized thus reducing rig torque enough so the relatively low powered turbine could drive the rig to the design speed of 24,000 rpm. This low flow of vapor coolant did adequately cool the bearing. It was thermally stable and didn't show any significant distress. Figure 6 shows the excellent condition of the test bearing after the 10 hours LOX test.

HIGH SPEED LH_2 BEARING DEVELOPMENT

In a related program, high speed ball bearing performance was demonstrated in LH_2. A 55mm bore diameter split inner ring angular contact ball bearing with an aluminum shrouded Salox M retainer was designed and tested at 40,000 rpm. Six bearings were tested for 10 hours each at a thrust load of 500 lbs. with 0.25 lbs/sec. of LH coolant flow. All bearings successfully completed this program with no significant distress. Figure 7 shows the excellent condition of this bearing after 10 hours at 2.2 MDN in LH_2.

Reference Contracts:

1. NAS8-5623 & NAS8-15494 RL10
2. NAS3-7943 Advanced Bearing Study
3. NAS8-11537 Research and Development of Materials for Use As Lubricants In a Liquid Hydrogen Environment
4. NAS8-20540 350K LOX Pump Development
5. NAS8-11714 350K LH_2 Pump Development

Table 2 Summary of Candidate Lubricant Materials

Candidate	Description	Equivalent MDN	Test Time (Max 10 hrs.)	Insert Wear
Baseline	Silicon filled Teflon (Rulon A)	4	10	Medium
1.	Bronze-Pb-PTFE on steel strip	4	4.6	High
2.	Bronze Filled Teflon (40/60 wt. Salox M)	4	10	Low
3.	MoS_2 filled teflon (15/85 wt.)	2	5.5	Very High
4.	Ag-MoS_2 matrix (80/20 vol.)	4	10	High
5.	Al-MoS_2 matrix (80/20 vol.)	2	6.6	High
6.	Ag-CaF_2 matrix (80/20 vol.)	2	3.5	Very High
7.	Boron Nitride	2	5.5	Very High
8.	Rulon A with MLF-5 on races	4	10	Low
9.	MoS_2 -filled Polyimide (15/85 wt.)	4	4.7	High
10.	Rulon A with fluorocarbon on races	4	4.5	High (coating built up)
11.	Cu-MoS_2 filled polyimide (20/10/70 vol.)	4	0.3	Very High
12.	Ni-MoS_2 matrix (80/20 vol.)	4	3	Very High
13.	Bronze with MLF-5 on races	4	0.3	Very High (coating wore off)
14.	Bronze filled Polyimide (20/80 vol.)	4	9	High

15.	Bronze filled Polyimide (30/70 vol.)	4	10	Medium
16.	Polyimide, unfilled	4	7	Very High
17.	Bronze filled Polyimide (40/60 vol.)	4	10	Low
18.	MoS_2 impregnated Ag (sintered fibers)	4	9.6	High
19.	MoS_2 impregnated Bronze (sintered fibers)	4	0.2	Very High
20.	Ag-WSe_2 filled Polyimide (75/5/20 vol.)	4	10	Low

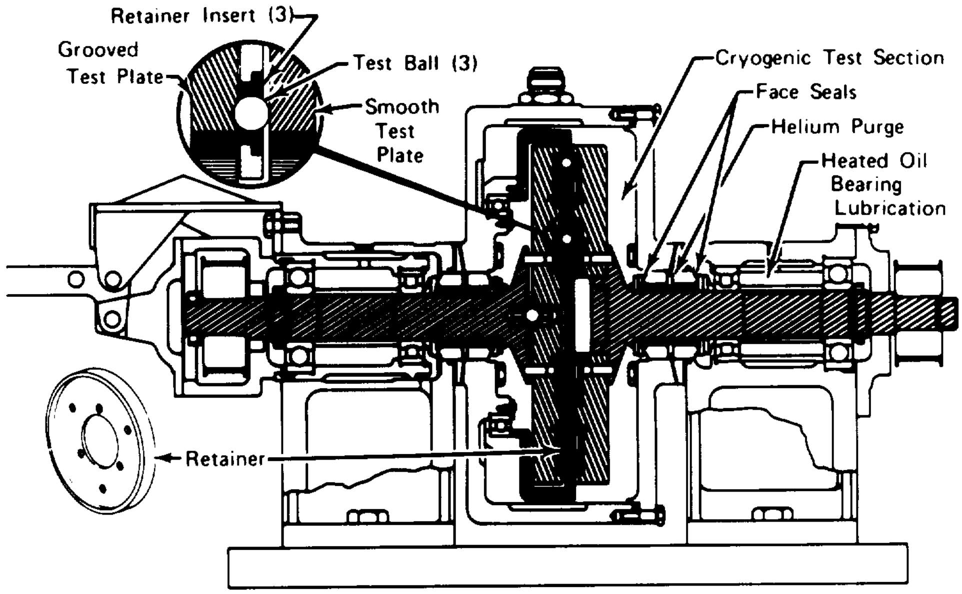

Figure 1 - Ball-plate test rig. Used for retainer material testing under conditions similar to actual bearing applications. Counter rotating plates simulates the ball rotational speed and ball spin without the high centrifugal loads typical in a high speed bearing.

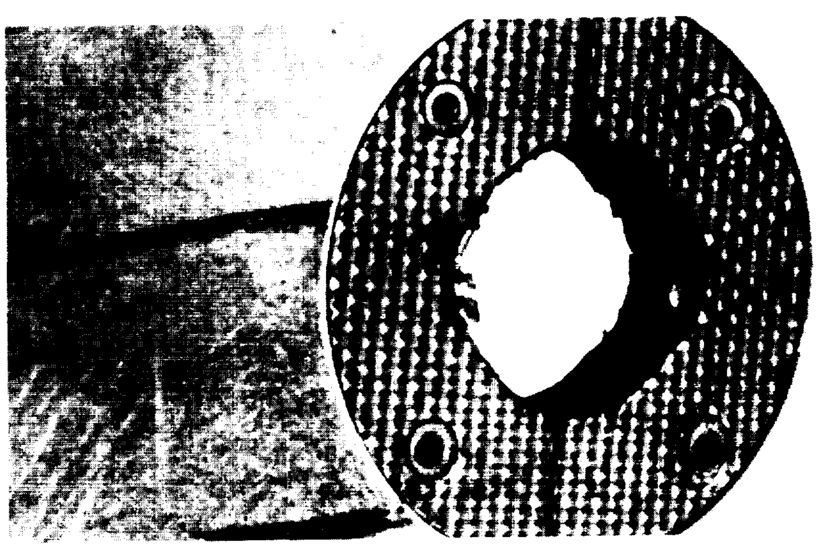

Figure 2 - Typical candidate material retainer insert in the rig retainer showing test induced pocket wear. Insert shown is Armalon after 12 hrs. and 25 min. of test.

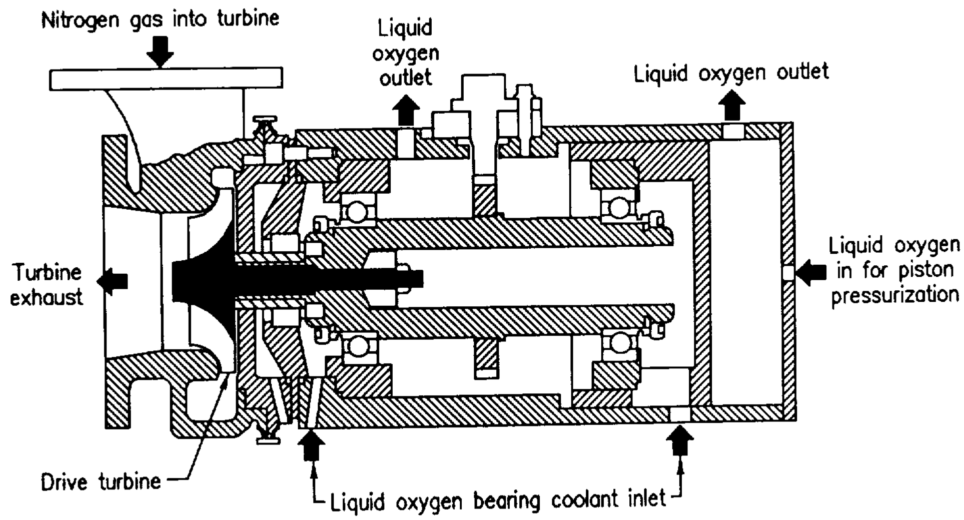

Figure 3 - Turbine driven test rig used for testing cryogenic ball bearings. This is shown for use with LOX, similar rigs were also used for LH_2 cooled bearings.

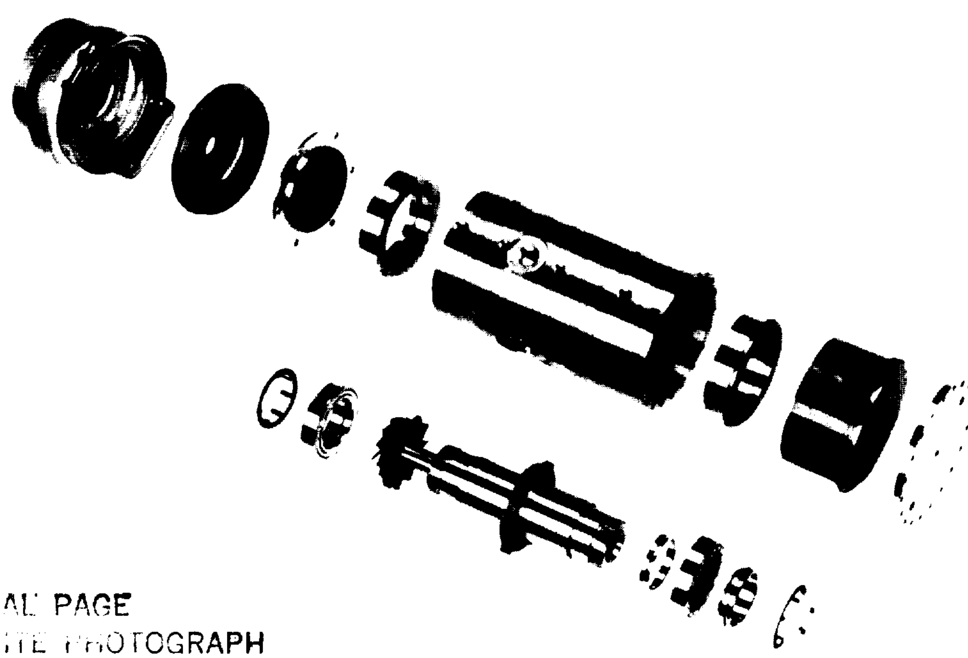

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Figure 4 - Rig parts displayed with two 50mm bore ball bearings tested in LOX.

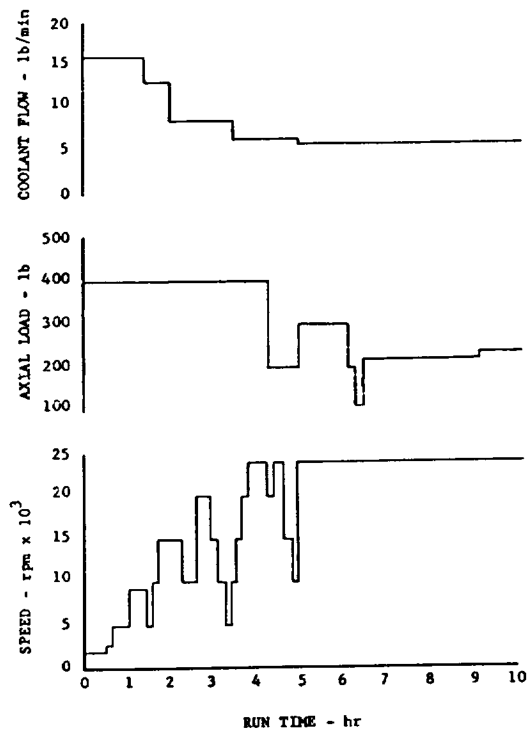

Figure 5 - Summary of the test conditions used for the 10 hr. LOX test.

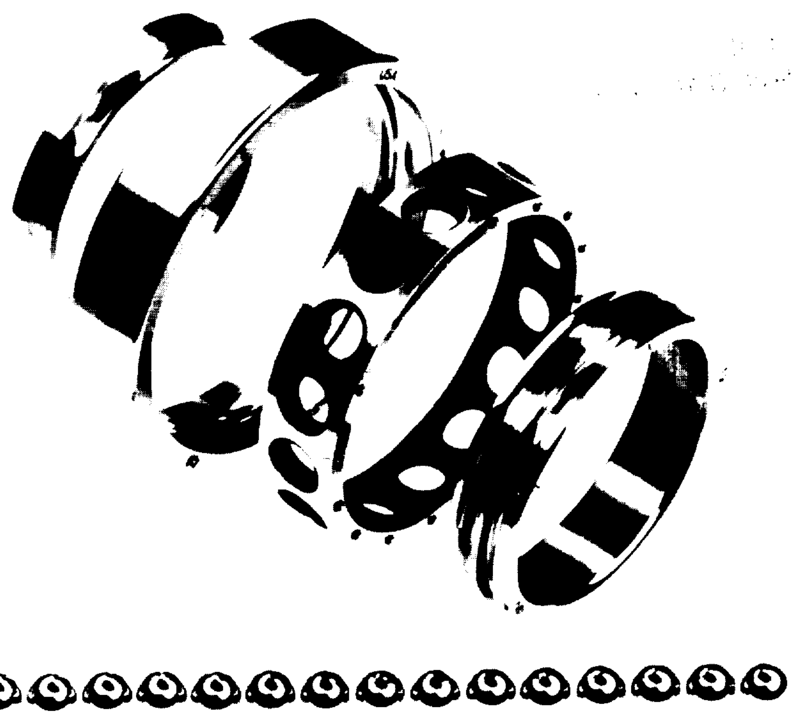

Figure 6 - This is the 50mm bore ball bearing showing the excellent post test condition after 10 hrs. in LOX, including 5 hrs. at 1.2 MDN.

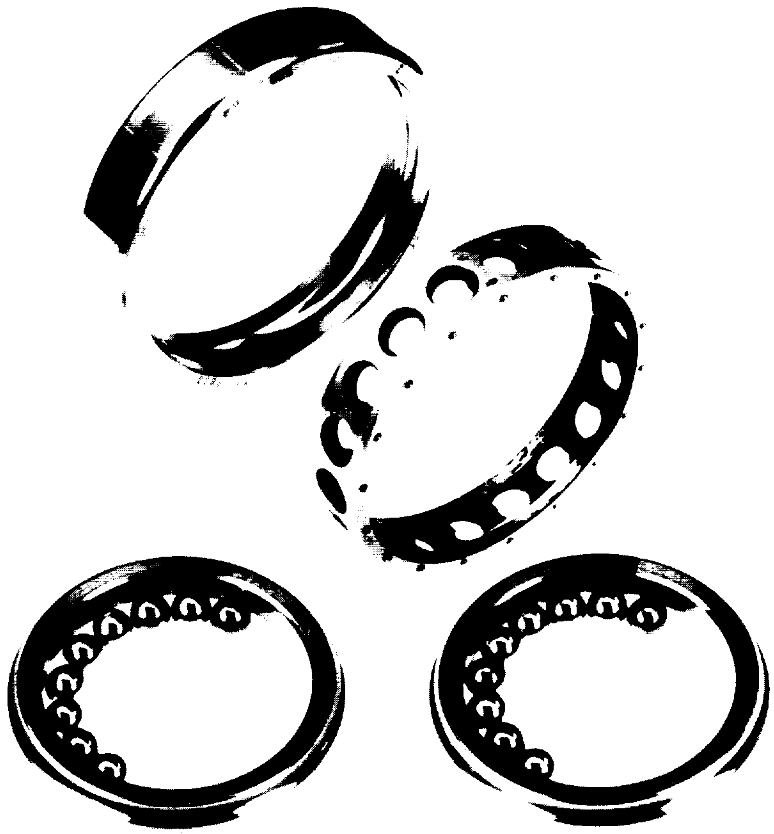

Figure 7 - This 55mm bore ball bearing is in excellent condition after 10 hrs. in LH_2 at 40,000 rpm, which is 2.2 MDN.